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RESEARCH MEMORANDUM

AN ANALYSIS OF A HIGHLY COMPOUNDED TWO-STROKE-CYCLE
COMPRESSION-IGNITION ENGINE

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and Arnold E. Biermann

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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AN ANALYSIS OF A HIGHLY COMPOUNDED TWO-STROKE-CYCLE

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SUMMARY

The results of an analysis of a compound two-stroke cycle, compression-ignition engine operating under such conditions that the turbine delivers a large amount of the useful work of the cycle are presented.

Under these conditions, specific weights for the power plant of under 1.0 pound per brake horsepower may be obtained with reasonable values of peak cylinder pressure and turbine-inlet temperature. Desirable manifold pressures are in the range of 60 to 110 pounds per square inch absolute at an altitude of 30,000 feet. A pay-load - range study for an aircraft using the power plant considered serves to evaluate the merit of the engine and indicates large increases in range over that offered by the conventional reciprocating engine, which is not compounded.

INTRODUCTION

Previous investigations of the lightly compounded reciprocating engine (references 1 to 8) have indicated that the advantage of good fuel economy in this type of power plant is, to a certain extent, offset by a high specific weight. The lightly compounded engine is defined as one in which the greater part of the work of the cycle is performed by the reciprocating-engine component. The reciprocating-engine component is relatively heavy as compared with the gas-turbine component; consequently, the over-all weight of the lightly compounded engine is high. It is therefore advantageous in the compound engine for the gas turbine to perform as much of the work of the cycle as is consistent with the attainment of high over-all efficiency. This arrangement results in a highly compounded engine in which the reciprocating engine performs only the work of the cycle that involves high pressures and high temperatures. The reciprocating

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engine can therefore be made relatively small, and inasmuch as this component represents the greater part of the weight of the compound engine, the over-all weight of the compound engine is low.

An analysis of a compound engine using a spark-ignition cycle over a wide range of compounding is presented in reference 9. In this analysis, however, the degree of compounding is treated as a dependent variable and weight is not discussed. The analysis is also restricted to one set of engine limits and does not consider the knock or preignition problems.

In reference 10, a particular case of the highly compounded engine in which the power developed by the reciprocating engine is equal to the power required by the compressor is analyzed. In this analysis, the degree of compounding is fixed at one value for any given set of engine limits and engine operating conditions. In addition, the division of work must change to maintain the compressor-engine power equality whenever the operating conditions or engine limits are changed. Consequently, the analysis of reference 10 cannot show trends with division of work and cannot lead to conclusions regarding the effect of division of work on the performance of the engine.

The two-stroke-cycle, compression-ignition engine has certain unique characteristics that make it especially suitable for a highly compounded engine. Among these characteristics are:

(a) The fuel-knock and preignition problems of the spark-ignition engine are avoided.

(b) The capacity of the compression-ignition engine for operating with lean mixtures makes control of both the turbine-inlet temperatures and the cylinder pressures feasible to some extent by varying the mixture strength.

(c) The high air-handling capacity of the two-stroke-cycle engine is of particular advantage in reducing the weight of the compound engine. The compression-ignition engine is well adapted to operate on the two-stroke cycle.

(d) The absence of poppet valves in the two-stroke-cycle engine cylinder makes it capable of withstanding high cylinder pressures.

The use of the simple loop-scavenged cylinder is complicated by the difficulty of scavenging such a cylinder. A uniflow-scavenged cylinder offsets this difficulty, but such a cylinder incurs a penalty in engine weight and complication.

The potentialities of the compound, two-stroke-cycle, compression-ignition engine when the degree of compounding is increased have therefore been analytically investigated at the NACA Lewis laboratory and are indicated herein. Because the performance of the highly compounded engine is dependent upon the values assigned to the parameters that determine the mechanical and thermal stresses in the engine and the efficiencies of the various components in the system, the performance potentialities of this engine when the engine limits and component efficiencies are varied are also shown.

METHODS OF ANALYSIS

The engine used in the analysis comprises a two-stroke cycle, compression-ignition engine, a compressor, and a turbine geared to a common shaft (fig. 1). Initial compression takes place in a diffuser and the compressor; final compression, addition of fuel, and initial expansion occur in the component reciprocating engine. Final expansion occurs in the turbine and the exhaust nozzle. The degree of compounding is determined by the amount of compression and expansion taking place in the component engine relative to that which occurs in the compressor and the turbine.

Performance Analysis

The engine was assumed to operate in NACA standard atmospheric conditions at a flight speed of 400 miles per hour. Except where specifically stated, an altitude of 30,000 feet was assumed. Full ram temperature rise and 90 percent of the available ram pressure rise at the inlet to the compressor were assumed, and jet thrust from the turbine exhaust was neglected to reduce the number of variables.

The following table shows the independent variables considered and the ranges through which they were assumed to vary:

Variable	Basic values	Range considered
Peak cylinder pressure, lb/sq in. abs.	1200, 1600	1000 - 2000
Turbine-inlet temperature, °R	1860, 2260	1400 - 2400
Manifold pressure, lb/sq in. abs.	60, 110, 160	20 - 200
Altitude, feet	30,000	0 - 50,000
Compressor efficiency	0.85	0.60 - 0.95
Component-engine thermal efficiency	Standard ^a	0.60 - 1.05
Turbine efficiency	0.85	X standard 0.60 - 0.95

^aStandard component-engine efficiency is that defined by the data of fig. 2.

The basic values are the values at which each variable was held fixed while the other variables were varied.

Component engine. - The component engine was assumed to operate on a limited-pressure combustion cycle. A search of data on compression-ignition engines indicated that the ratio between the combustion pressure and the compression pressure could be expressed as a linear function of a cylinder fuel-air ratio. The linear function chosen for this analysis is shown in figure 2. This relation was subsequently used to calculate peak cylinder pressures in the component engine. Because the component-engine indicated thermal efficiency is relatively unaffected by changes in inlet-manifold temperature (or temperature at end of compression), the effect of variations of this temperature on component-engine efficiency was neglected.

The efficiency data in figure 2 were obtained by computing an ideal efficiency for the chosen cycle and subsequently correcting this ideal efficiency to an actual value. In carrying out this procedure, the methods of Hersey, Eberhardt, and Hottel (reference 11) were used for the rich mixtures, and an air-cycle analysis was used for the lean-mixture points. Allowance was made for the presence of residuals in the cylinder. An indicated basis was used to permit a correlation with four-stroke-cycle data. The resultant efficiency data were then correlated with the data of reference 12. The factor used to correct the data varied linearly with fuel-air ratio and was weighted with respect to compression ratio. The method of correction is discussed in greater detail (in the notation of appendix A) in appendix B.

Turbine. - The turbine-inlet temperature was determined by means of a heat balance across the engine with an assumed heat

loss of 18 percent of the heat input of the fuel. The turbine-inlet temperature and the turbine work were evaluated by Mollier charts of the thermodynamic properties of exhaust gases, plotted from the data of reference 13.

Performance limits. - The chief limitations on the performance of the engine were taken to be peak cylinder pressure and turbine-inlet temperature. A graphical solution was used to find values of fuel-air ratio and compression ratio that would result in the desired turbine-inlet temperature. Consequently, the analysis was made with compression ratio as the independent variable but is reported with turbine-inlet temperature as a parameter.

A third limitation influential in fixing the engine performance is mean piston speed. Because increases in piston speed are largely accompanied by increases in scavenging pressure drops and friction losses, piston speed in this analysis was held constant at 2400 feet per minute.

A summary of the equations used in evaluating the performance of the compound engine is presented in appendix B.

Weight Analysis

A dimensional analysis was made on each component of the compound engine to establish weight equations for that component. The constants of the resulting expressions were evaluated by a comparison with unpublished data from current reciprocating, turbojet, and turbine-propeller engines and turbosuperchargers. All weights (the installed weights of the power plant without propeller) were calculated for an engine of 3000 brake horsepower.

The weight of the component engine was set up as a function of the peak cylinder pressure and displacement and, for a given cylinder pressure and displacement, was 30 to 40 percent greater than that of a comparable spark-ignition engine. This increase was deemed necessary to allow for the additional weight incurred in the use of the two-stroke-cycle, uniflow-scavenged cylinder.

For the compressor and turbine components, the weight was assumed to be a function of the volumetric flow rate and the pressure ratio. The weight of the propeller- and turbine-reduction gears was taken to be proportional to the horsepower transmitted. Radiator weights were expressed as a function of the fuel flow.

The equations used in this part of the analysis are summarized in appendix C.

Pay-Load - Range Analysis

In evaluating the performance of the engine as installed in an aircraft, the pay-load - range analysis of reference 14 was used. A wing loading limited to 80 pounds per square foot was selected. A propeller specific weight of 0.5 pound per brake horsepower and an engine frontal area of 14.72 square feet were used. All other assumptions pertaining to the aircraft are as given in reference 14.

RESULTS AND DISCUSSION

Effect of Degree of Compounding

In an examination of the over-all performance of the two-stroke-cycle, compression-ignition compound engine, investigation of the methods whereby low specific weights may be obtained is particularly desirable. Obviously, one way of accomplishing this consideration is to increase the degree of compounding of the engine. This increase is most easily attained by raising the manifold and exhaust pressures of the component engine and at the same time so decreasing the compression ratio and the fuel-air ratio as to permit consistent values of cylinder pressure and turbine-inlet temperature. In this manner, the temperature ratio across the compressor and the turbine, relative to that occurring within the component engine, is increased.

The variation in specific output (bhp/cu in. of total cylinder volume above the ports), specific air flow (lb/(hr) (cu in. of total cylinder volume above the ports)), and specific air consumption (lb/bhp-hr) when the degree of compounding is altered at an altitude of 30,000 feet is shown in figure 3. The amount of compounding is indicated in figure 3 by the manifold pressure shown as the abscissa. As the manifold pressure is increased, the specific air flow through the reciprocating engine is increased. Leaning the fuel mixture, however, causes an increase in the specific air consumption. Immediately, the question arises as to whether the increase in air capacity is sufficient to offset the increase in specific air consumption. This question is answered by the specific-output curve of figure 3, which initially rises quite rapidly and reaches a peak value.

Beyond the value of manifold pressure corresponding to this peak, the specific air consumption increases more rapidly than the air-flow rate, which causes a reduction in specific output.

It has been intimated previously that the weight of the reciprocating component engine is influential in fixing the weight of the compound engine. In other words, the weight of the component engine is large compared with the combined weight of the turbine and compressor components. If this relation is true, the weight of the compound engine per cubic inch of component-engine-cylinder volume should not vary too much with the degree of compounding. Data to illustrate this point are shown in figure 4, in which the weight of the compound engine per cubic inch of component-engine-cylinder volume is plotted as a function of manifold pressure. The increasing magnitude of this variable as the manifold pressure is increased is, of course, caused by the increase in the weights of the turbine, the compressor, and the turbine-reduction gear.

The data of figures 3 and 4 show the fundamental reason why the highly compounded engine is lighter on a specific-weight basis than the lightly compounded engine. Because the quotient of the values of weight per unit cylinder volume and power per unit cylinder volume is specific weight in weight per unit of power, it is obvious that the specific weight will decrease when the algebraic rate of change of the specific output with a change in operating conditions is larger than the algebraic rate of change of engine weight per unit of cylinder volume. The data of figures 3 and 4 show that an increase in the degree of compounding satisfies these conditions.

Specific output, specific weight, and specific fuel consumption are plotted in figure 5 as functions of the degree of compounding, again represented by manifold pressure. The degree of compounding is also given for this range of manifold pressure. The degree of compounding is defined as the turbine work divided by the sum of the engine and turbine work. Thus, a value of zero represents an ordinary reciprocating engine without a turbosupercharger and a value of unity is a turbine-propeller engine. These curves show that operation in the region of minimum fuel consumption and engine weight occurs around a manifold pressure of 60 pounds per square inch absolute for the lower limits and around 110 pounds per square inch absolute for the higher limits. The degree of compounding for operation at these manifold pressures increases with the engine limits.

The fuel-consumption curves of figure 5 reach a minimum value at moderate values of manifold pressure. Because the turbine-inlet temperature is constant, increases in the manifold pressure incur a rise in turbine pressure ratio and thus an increased energy recovery in the turbine. Increasing the manifold pressure at constant engine limits, however, reduces the expansion ratio in the component engine. This expansion ratio varies from a maximum value of about 18 at the lower manifold pressures to a minimum of about 4 at the higher manifold pressures. The sum of these effects causes the fuel consumption to decrease initially and then increase.

The data of figure 5 indicate that the highly compounded engine is capable of operation at brake specific fuel consumptions of the order of 0.32 pound per horsepower-hour and specific weights below 0.8 pound per brake horsepower. These values are for a peak cylinder pressure of 1600 pounds per square inch and a turbine-inlet temperature of 2260° R.

In figure 6 the work of the various components is shown as a function of manifold pressure for the data of figure 5. These variations in component work lead to the division of work shown in figure 5. The point at which the engine and compressor work curves intersect corresponds to the operating point of a gas-generator engine of the type discussed in reference 10. This point occurs at a manifold pressure of 75 pounds per square inch absolute for the lower engine limits (fig. 6(a)), and at 100 pounds per square inch absolute for the higher limits (fig. 6(b)).

Effect of Altitude

The performance of a highly compounded engine is shown as a function of altitude for three values of manifold pressure in figure 7. These data show that up to about 30,000 feet, a change in altitude has little effect on the specific weight of the engine. At the same time, a pronounced decrease in fuel consumption is noted as the altitude of operation is increased. This decrease is a result of maintaining a constant limiting cylinder pressure. The over-all pressure ratio of the compound engine thus increases in direct relation to the reduction in ambient pressure with altitude, which results in a lower fuel consumption.

The specific output decreases slowly up to about an altitude of 35,000 feet and then drops more rapidly as the altitude is increased further. Both the specific air flow and specific air consumption decrease as the altitude of operation is increased, and these two variables tend to compensate each other and maintain an

essentially constant specific output. Above 35,000 feet, however, the ambient-air temperature reaches a constant value. As a result, the specific air consumption decreases at a slower rate and the specific air flow decreases at a higher rate with further altitude increases, and so the slope of the specific-output curve changes.

Effect of Component Efficiencies

Compressor efficiency. - The influence of compressor efficiency on over-all engine performance at an altitude of 30,000 feet is shown in figure 8. Specific fuel consumption is more or less independent of the compressor efficiency because inefficiencies in the compressor are partly recovered by the turbine that follows in the cycle and because some compression takes place in the component engine. The specific weight and the specific output, however, show a more marked variation for changes in compressor efficiency.

Thermal efficiency of the reciprocating engine. - In figure 9, the performance of the compound engine at an altitude of 30,000 feet is given as a function of relative thermal efficiency. Relative thermal efficiency is defined as the ratio between the actual thermal efficiency of the reciprocating engine and that defined by the data of figure 2. Here again, the same general effects are noted as for inefficiencies occurring in the compressor. The specific fuel consumption varies slightly with wide changes in relative thermal efficiencies, whereas the variation in specific weight and specific output is again more predominant.

Turbine efficiency. - As might be expected, the variation of engine performance with turbine efficiency at 30,000 feet (fig. 10) is rather marked. Because in the highly compounded engine a large portion of the work of the cycle is performed in the turbine, changes in turbine efficiency are critical with respect to over-all engine performance. Figure 10 indicates that a change in turbine efficiency from 70 to 90 percent decreases the fuel consumption about 22 percent at a manifold pressure of 110 pounds per square inch absolute. The corresponding change in specific weight is about 13 percent, and that in specific output 25 percent.

Variation of Engine Performance with Engine Operating Limitations

Figures 11 to 13 show engine performance at an altitude of 30,000 feet as a function of the engine operating limits, peak cylinder pressure and turbine-inlet temperature, for three manifold pressures.

The general effect of raising the engine limits, as shown by these curves, is to increase the performance of the engine. The specific output (fig. 13) and the specific weight (fig. 12) generally improve with increases in either or both of the engine limits. Figure 11, however, shows that the specific fuel consumption passes through a minimum value with variable turbine-inlet temperature. The shape of these curves is influenced by the magnitudes of the compressor and turbine efficiencies and the manifold pressure. At low values of turbine-inlet temperature, the effect of compressor efficiency is predominant; whereas, at high values of this temperature, the turbine efficiency is more influential in determining the fuel consumption.

An inspection of a composite figure of figures 11 to 13 for the various manifold pressures shows that the surfaces for specific fuel consumption and specific weight for the different manifold pressures intersect. The general effect is for optimum operation to occur at higher manifold pressures as the engine limits are increased.

The data shown in these figures indicate that the desired engine performance may sometimes be obtained with several combinations of limits. Thus the difficulty of operating with a high turbine-inlet temperature might be weighed against the problems encountered in using high peak cylinder pressures. The presence of a third variable, that of manifold pressure, further complicates the situation. The selection of the best engine limits, therefore, requires a delicate compromise involving the application of the engine, the probable cost of development, and the required operating reliability of the compound engine.

Effect of Engine Limits on Aircraft Performance

Specific weight and specific fuel consumption alone do not determine the merit of an engine unless some means is available to ascribe the proper importance to each. Such a means is

afforded by an analysis of the performance of the aircraft in which the engine is used. For the present purposes, pay-load-carrying ability at long range was selected as the criterion of excellence inasmuch as the highly compounded engine is proposed mainly for long-range flight.

The effect of engine limits, peak cylinder pressure, and turbine-inlet temperature on the disposable-load - gross-weight and initial-fuel-rate - gross-weight ratios of a typical transport-type aircraft is shown in figure 14. The analysis and the assumptions leading to these data were taken from reference 14; an engine frontal area of 14.72 square feet and a propeller specific weight of 0.5 pound per brake horsepower were assumed. The parameter K may be defined as the ratio of average to initial fuel rate per mile per ton of initial gross weight. These curves provide a means of evaluating the relative importance of the engine limits as they influence the performance of the aircraft in which the engine is used. For example, figure 14 shows that as far as ultimate range is concerned, there are many combinations of peak cylinder pressure and turbine-inlet temperature that result in the same value of ultimate range. When a large pay load is to be carried, however, the data show that the higher turbine-inlet temperature should be favored.

Figure 14 shows that increasing the peak cylinder pressure results in an increase in the ultimate range. This effect occurs through a reduction in the initial-fuel-rate - gross-weight ratio, although in almost every case, slight increases in the disposable-load - gross-weight ratio are also present. This increase in ultimate range indicates that an increase in cargo load at a given range may be obtained by operating at higher cylinder pressures.

Maximum ultimate range is obtained at a given value of turbine-inlet temperature for each manifold pressure and decreases when the temperature is changed. Maximum ultimate range for any given cylinder pressure occurs at the point where the range line and constant-cylinder-pressure line are tangent in figure 14. The turbine-inlet temperature at this point varies from about 1700° R at a manifold pressure of 60 pounds per square inch absolute to about 2200° R at 160 pounds per square inch absolute. The magnitude of the peak cylinder pressure also has a small effect on the location of this optimum point.

Increasing the turbine-inlet temperature in all cases raises the disposable-load - gross-weight ratio. Temperatures above the optimum temperature for maximum ultimate range are therefore desirable for operation with large cargo loads.

The pay-load - gross-weight ratio, taken from figure 14, is plotted against turbine-inlet temperature in figure 15 for a peak cylinder pressure of 1600 pounds per square inch. The peaks in these curves indicate optimum turbine-inlet temperature for maximum cargo capacity, and the dashed line connecting these peaks therefore represents the optimum variation of turbine-inlet temperature with aircraft range. As the range increases, the optimum turbine-inlet temperature decreases from a value corresponding to that for the maximum disposable-load - gross-weight ratio to a value corresponding roughly to that for the minimum initial-fuel-rate - gross-weight ratio.

The data in figures 14 and 15 show that the highly compounded engine is capable of operating at ultimate ranges up to 10,000 miles (fig. 14) and at pay-load - gross-weight ratios as high as 0.475 at short ranges (fig. 15). Reasonably high values of engine limits are imperative, however, in order for the engine to approach this performance.

For the interpretation of the range and cargo-capacity values cited for the highly compounded engine, the performance of an aircraft powered with a conventional turbosupercharged reciprocating engine was calculated. This conventional engine was assumed to have a specific weight of 2.0 pounds per brake horsepower installed but without a propeller and a specific fuel consumption of 0.45 pound per brake horsepower-hour. The resultant values for this aircraft - power-plant combination were an ultimate range of 5500 miles and a pay-load - gross-weight ratio of 0.36 at short range. Thus the highly compounded engine provides about double the range and about 30 percent greater cargo capacity than the more conventional engine. As the range increases, the ratio of cargo capacities for the two aircraft increases in favor of the aircraft powered by the highly compounded engine, reaching infinity at 5500 miles range.

CONCLUSIONS

From an analysis of a highly compounded two-stroke-cycle, compression-ignition engine, the following conclusions may be drawn:

1. The highly compounded engine is capable of operating at a specific fuel consumption of the order of 0.32 pound per brake horsepower-hour and a specific weight of the order of 0.8 pound per brake horsepower, with reasonable values of peak cylinder pressure and turbine-inlet temperature.

2. Desirable manifold pressures are in the range of 60 to 110 pounds per square inch absolute at an altitude of 30,000 feet.

3. The performance potentialities of the highly compounded engine are improved as pressure and temperature limitations are increased.

4. Moderate inefficiencies in the component compression-ignition engine and in the compressor can be tolerated in the highly compounded engine because these losses are partly recovered by the turbine that follows in the cycle.

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APPENDIX A

SYMBOLS

The following symbols are used in appendixes B and C:

$c_{p,c}$	specific heat at constant pressure of compressor air, 0.243 Btu/(lb)(°R)
F/A	over-all fuel-air ratio
$(F/A)_b$	fuel-air ratio in cylinder of component engine (burner)
H_e	enthalpy of gases entering turbine, Btu/lb
H_t	enthalpy of gases leaving turbine, Btu/lb
H_m	enthalpy of air entering component engine, Btu/lb
h_b	lower heat of combustion of fuel, 18,500 Btu/lb fuel
M	mass flow of air through engine, lb/(sec)(cu ft of cylinder volume above ports)
N	speed of component engine, rpm
P_a	ram pressure of air at entrance to compressor, lb/sq in. abs.
P_b	compression pressure of component engine (burner), lb/sq in. abs.
P_e	exhaust back pressure of component engine (turbine-inlet pressure), lb/sq in. abs.
P_m	inlet-manifold pressure of component engine, lb/sq in. abs.
P_{max}	peak combustion pressure of component engine, lb/sq in. abs.
P_0	pressure of ambient air, lb/sq in. abs.
Q	heat loss of component engine, Btu/lb of air entering engine
R_s	scavenging ratio - ratio of weight of fresh charge delivered to component-engine cylinder per cycle to product of inlet density and total cylinder volume above ports

r	compression ratio of component engine
T_a	temperature of air at entrance to compressor, °R
T_e	temperature of gases entering turbine, °R
T_m	temperature of air entering component engine (burner), °R
T_0	temperature of ambient air, °R
V	velocity of flight, mph
v_a	volume flow of air into compressor, cu ft/sec
v_b	total piston displacement of component engine (burner), cu in.
v_e	volume flow into turbine, cu ft/sec
W_{acc}	weight of engine accessories, lb
W_b	weight of component engine, lb
W_c	weight of compressor, lb
W_{pr}	weight of propeller reduction gear, lb
W_r	weight of radiators, lb
W_t	weight of turbine, lb
W_{tr}	weight of turbine reduction gear, lb
w_b	brake output of component engine (burner), Btu/lb of air entering engine
w_c	compressor work, Btu/lb of air entering engine
w_n	net work of compound engine, Btu/lb of air entering engine
w_t	turbine work per pound of air, Btu/lb
η_b	indicated thermal efficiency of component engine (burner)
η_c	adiabatic efficiency of compressor

η_{pr}	efficiency of propeller reduction gearing, 0.97
η_s	scavenging efficiency - ratio of weight of fresh charge contained in component-engine cylinder at time of port closing to product of inlet density and total cylinder volume above ports
η_t	adiabatic efficiency of turbine, total to static pressure
η_{tr}	efficiency of turbine reduction gearing, 0.97

APPENDIX B

ANALYSIS OF COMPOUND-ENGINE PERFORMANCE

The following equations were used to estimate the performance of the two-stroke-cycle compound engine:

Ram pressure and temperature. - The ram pressure and temperature in the diffuser duct leading to the compressor inlet with a 90-percent ram-pressure-rise recovery are expressed by

$$P_a = P_0 \left(\left[1 + \frac{1.79}{T_0} \left(\frac{V}{100} \right)^2 \right]^{3.5} - 1 \right) 0.9 + 1 \quad (B1)$$

and

$$T_a = T_0 + 1.79 \left(\frac{V}{100} \right)^2 \quad (B2)$$

Compressor calculations. - The performance of the compressor on the basis of work done per pound of air handled can be expressed by

$$w_c = c_{p,c} (T_m - T_a) \quad (B3)$$

where

$$T_m = \frac{T_a}{\eta_c} \left[\left(\frac{P_m}{P_a} \right)^{0.283} - 1 \right] + T_a \quad (B4)$$

Scavenging ratio. - Analysis of data from experimental and production two-stroke-cycle engines indicates that the two-stroke-cycle cylinder can be replaced by an equivalent orifice with respect to air flow through the cylinder. In the range of operation considered, the air flow through the uniflow cylinder chosen for this analysis can then be represented by the equation

$$R_s = k \sqrt{(1 - P_e/P_m) T_m} \quad (B5)$$

where k is a constant that includes the area and the discharge coefficient of the equivalent orifice and also includes conversion

constants to make the units consistent. The value of k is really a function of piston speed; however, because in this analysis piston speed is held constant, the value of k remains unchanged. Evaluation of this constant by use of experimental data from an engine of the type chosen for this analysis resulted in the equation

$$R_s = 0.0981 \sqrt{(1 - P_e/P_m) T_m} \quad (B6)$$

In the present analysis, the value of the scavenging ratio R_s was fixed at 1.3. Equation (B6) may then be rearranged to permit a calculation of the exhaust-pressure - manifold-pressure ratio and subsequently the exhaust pressure.

Scavenging efficiency. - Analysis of data from a uniflow, two-stroke-cycle engine (reference 9) indicated that the scavenging efficiency of this type of engine could be related to the scavenging ratio by the equations

$$\eta_s = 0.75 R_s + 0.25 \left(1 - e^{-R_s}\right) \quad (B7)$$

where

$$R_s \leq 1.0$$

and

$$\eta_s = 0.75 + 0.25 \left(1 - e^{-R_s}\right) \quad (B8)$$

where

$$R_s \geq 1.0$$

Over-all fuel-air ratio. - The over-all fuel-air ratio can be expressed by the relation

$$\frac{F}{A} = \frac{(F/A)_b \eta_s}{R_s} \quad (B9)$$

Efficiency of component engine. - A uniflow, two-stroke-cycle compression-ignition engine was used as the component engine for this analysis. Because this engine must operate over a wide range of compression ratios and fuel-air ratios, an analytical or graphical relation between the engine indicated thermal efficiency and the fuel-air ratio, compression ratio, and ratio of peak combustion pressure to compression pressure is convenient.

A limited pressure cycle was chosen for the component engine and the rate of combustion was assumed to be a linear function of the cylinder fuel-air ratio such that the ratio of peak combustion pressure to compression pressure was a maximum of 1.5 at a fuel-air ratio of 0.0678 and 1 at a fuel-air ratio of 0. Thus

$$P_{\max} = P_b \left[1 + \frac{0.5 (F/A)_b}{0.0678} \right] \quad (B10)$$

By this relation, the theoretical indicated thermal efficiency of the component engine was computed on a fuel-air-cycle basis for the richer mixtures (0.05 to 0.06775) from thermodynamic charts according to the methods of reference 11 and on an air-cycle basis for the very lean fuel-air ratios.

Rich-mixture data taken on a compression-ignition engine (reference 12) operating at the same conditions of fuel-air ratio, compression ratio, and ratio of peak combustion pressure to compression pressure were used to correct the theoretical indicated thermal efficiencies to actual thermal efficiencies. Because data were available for only one operating point, corrections for any other point were made on the assumption that the deviation of the actual from the theoretical thermal efficiency was proportional to the fuel-air ratio and the absolute magnitude of the point to be corrected.

Curves of actual indicated values of thermal efficiency η_b as a function of fuel-air ratio and compression ratio are shown in figure 2. The brake output in Btu per pound of air entering the engine, with a mechanical efficiency of 90 percent assumed, is then

$$w_b = \eta_b (F/A) (18,500) (0.9) \quad (B11)$$

The value of η_b is determined from figure 2 at the engine compression ratio used and the fuel-air ratio existing in the engine cylinder.

Turbine-inlet pressure. - The pressure at the inlet of the turbine may be expressed by the equation

$$P_e = P_m \left[1 - \frac{1}{T_m} \left(\frac{R_g}{0.0981} \right)^2 \right] \quad (B12)$$

Turbine-inlet temperature. - If the component engine is isolated and treated as a steady-flow machine, the enthalpy of the gases entering the turbine may be found by a simple heat balance:

$$H_e = \frac{H_m + h_b (F/A) - Q - w_b}{1 + (F/A)}$$

The heat loss of the component engine Q in Btu per pound of air may be expressed as a percentage of the heat input. Data from reference 15 may be interpreted to indicate that the heat loss is approximately 18 percent of the heat input, so that

$$H_e = \frac{H_m + h_b (F/A) (1 - 0.18) - w_b}{1 + (F/A)} \quad (B13)$$

Thermodynamic charts were prepared from reference 13, from which T_e may be read at the computed value of H_e .

Turbine calculations. - The turbine work per pound of air entering the engine may be expressed by

$$w_t = \eta_t \left[1 + (F/A) \right] (H_e - H_l) \quad (B14)$$

where H_l is the enthalpy of the gases leaving the turbine after 100-percent-efficient adiabatic expansion to atmospheric pressure and may be found from the thermodynamic charts.

Total work per pound of air. - If the work of the turbine is greater than the work of the compressor, the total work of the compound engine per pound of air entering the engine is

$$w_n = \eta_{pr} \left[w_b + \eta_{tr} (w_t - w_c) \right] \quad (B15)$$

If the compressor work is greater than the work of the turbine, the total work per pound of air is then

$$w_n = \eta_{pr} \left(w_b + \frac{w_t - w_c}{\eta_{tr}} \right) \quad (B15a)$$

Brake specific fuel consumption. - The brake specific fuel consumption of the compound engine is expressed by

$$bsfc = \frac{2545 (F/A)}{w_n} \quad (B16)$$

Air flow through engine. - The weight flow of air entering the compound engine in pounds per second per cubic foot of total volume above the ports is

$$M = R_s \frac{N}{60} \left(\frac{144 P_m}{53.3 T_m} \right) \quad (B17)$$

Net brake horsepower per cubic inch. - The output of the compound engine expressed in brake horsepower per cubic inch of total volume above the ports is

$$\frac{bhp}{cu\ in.} = M w_n \times \frac{778}{550} \times \frac{1}{1728} \quad (B18)$$

Brake specific air consumption. - The brake specific air consumption of the compound engine can be expressed by

$$bsac = \frac{bsfc}{(F/A)} \quad (B19)$$

Specific air flow. - The specific air flow, in pounds per hour per cubic inch, of the compound engine is

$$saf = (bhp/cu\ in.)\ bsac \quad (B20)$$

APPENDIX C

ANALYSIS OF SPECIFIC WEIGHT OF COMPOUND ENGINE

The specific weights in this analysis are computed for a compound engine having a rating of 3000 horsepower at an altitude of 30,000 feet. The component engine is assumed to operate at 2400 rpm and the limiting conditions of peak cylinder pressure and turbine-inlet temperature are given for each set of operating conditions.

The specific weight of the engine at each operating point is determined by estimating the weight of each component, adding the weights, and dividing by the rated 3000 horsepower. The results are then presented in pounds per horsepower.

Component engine. - Analysis of data giving the weights of the power sections of various production-type reciprocating engines indicated that the weight of an engine of given piston displacement would consist of (1) a basic frame weight, which would exist even though gas forces on the pistons were zero, (2) a factor to take into account the gas forces on the pistons, and (3) weights of accessory parts such as the generator, starter, pumps, fuel injectors, and tubing. The equation of total engine weight then takes the form:

$$W_b = \left(k_1 + k_2 P_{\max} \right) v_b + W_{\text{acc}}$$

From consideration of data from current engines and from reference 16 and with the weight of accessories assumed at approximately 200 pounds, the constants k_1 and k_2 may be evaluated so that

$$W_b = \left(0.5 + \frac{0.5 P_{\max}}{1600} \right) \frac{v_b}{1.25} + 200 \quad (C1)$$

If the ratio of compression ratio based on the volume above the ports to the compression ratio based on the total piston displacement is assumed to be 0.8, the total piston displacement v_b may be calculated from the equation

$$v_b = \frac{3000}{\text{bhp/cu in.}} \cdot 1.25 \left(\frac{r - 0.8}{r} \right) \quad (C2)$$

Compressor and turbine weights. - Analysis of data on current compressors and turbines indicates that the weights of these flow machines consist of: (1) a basic frame weight, (2) a factor that takes into account the volume flow, and (3) a factor that accounts for the number of pressure stages required.

Dimensional analysis shows that, on the basis of constant velocity into the flow unit, volume flow through the unit is proportional to the diameter squared and weight of the unit is proportional to the diameter cubed. Thus the weight of the flow machine is a function of the volume flow to the 1.5 power. Further, inasmuch as the weight of the compressor or turbine is proportional to the number of stages required and the total pressure ratio across the unit is equal to the product of the pressure ratios across each stage, the weight of the compressor or the turbine is a function of the log of the total pressure ratio.

As a result of evaluating the constants in the equation relating these parameters by means of data from current compressors and turbines, the weight of the compressor is expressed by

$$W_c = 75 + 0.0353 v_a^{1.5} \log_{10} \left(\frac{P_m}{P_a} \right) \quad (C3)$$

and the weight of the turbine is expressed by

$$W_t = 36 + 0.042 v_e^{1.5} \log_{10} \left(\frac{P_e}{P_o} \right) \quad (C4)$$

The volume flow entering the compressor, expressed in cubic feet per second at compressor-inlet conditions, is

$$v_a = \frac{3000}{\text{bhp/cu in.}} \times \frac{1}{1728} \times \frac{R N}{60} \times \frac{P_m}{T_m} \times \frac{T_a}{P_a} \quad (C5)$$

and the volume flow entering the turbine, expressed in cubic feet per second at turbine-inlet conditions, is

$$v_e = \frac{3000}{\text{bhp/cu in.}} \times \frac{1}{1728} \times \frac{R N}{60} \times \frac{P_m}{T_m} \times \frac{T_e}{P_e} \left(1 + \frac{F}{A} \right) \quad (C6)$$

Weight of reduction gears. - An examination of data on current turbine-engine reduction gears showed that their weight could be expressed as a fraction of the horsepower transmitted. Thus the weight of the propeller reduction gear of the compound engine is

$$W_{pr} = 0.15 \times 3000 \quad (C7)$$

and the weight of the turbine reduction gear of the compound engine is

$$W_{tr} = 0.15 (w_t - w_c) \frac{778}{550} \frac{3000}{\text{bhp/cu in.}} \frac{1}{1728} \frac{R_s N}{60} \frac{144}{53.3} \frac{P_m}{T_m} \quad (C8)$$

Weight of radiators. - The entire heat rejection of the component engine, which includes heat rejected to the coolant and to the lubricating oil, was assumed to be delivered to one set of radiators. Radiators having capacities of 6000 Btu per minute per square foot of area per 100° F of initial temperature difference and weights of 20 pounds per square foot of area were used in the calculations. With a total heat rejection of 18 percent of the fuel input to the engine and an average coolant temperature of 250° F, the weights of the radiator will then be

$$W_r = \frac{30,000 \times \text{bsfc}}{60} \times \frac{0.18 \times 18,500 \times 20 \times 100}{6000 \times (250 + 460 - T_a)}$$

or

$$W_r = \text{bsfc} \times 555 \times \frac{100}{(710 - T_a)} \quad (C9)$$

Specific weight of compound engine. - The specific weight of the compound engine can then be expressed by the equation

$$\text{specific weight} = \frac{W_b + W_c + W_t + W_{pr} + W_{tr} + W_r}{3000} \quad (C10)$$

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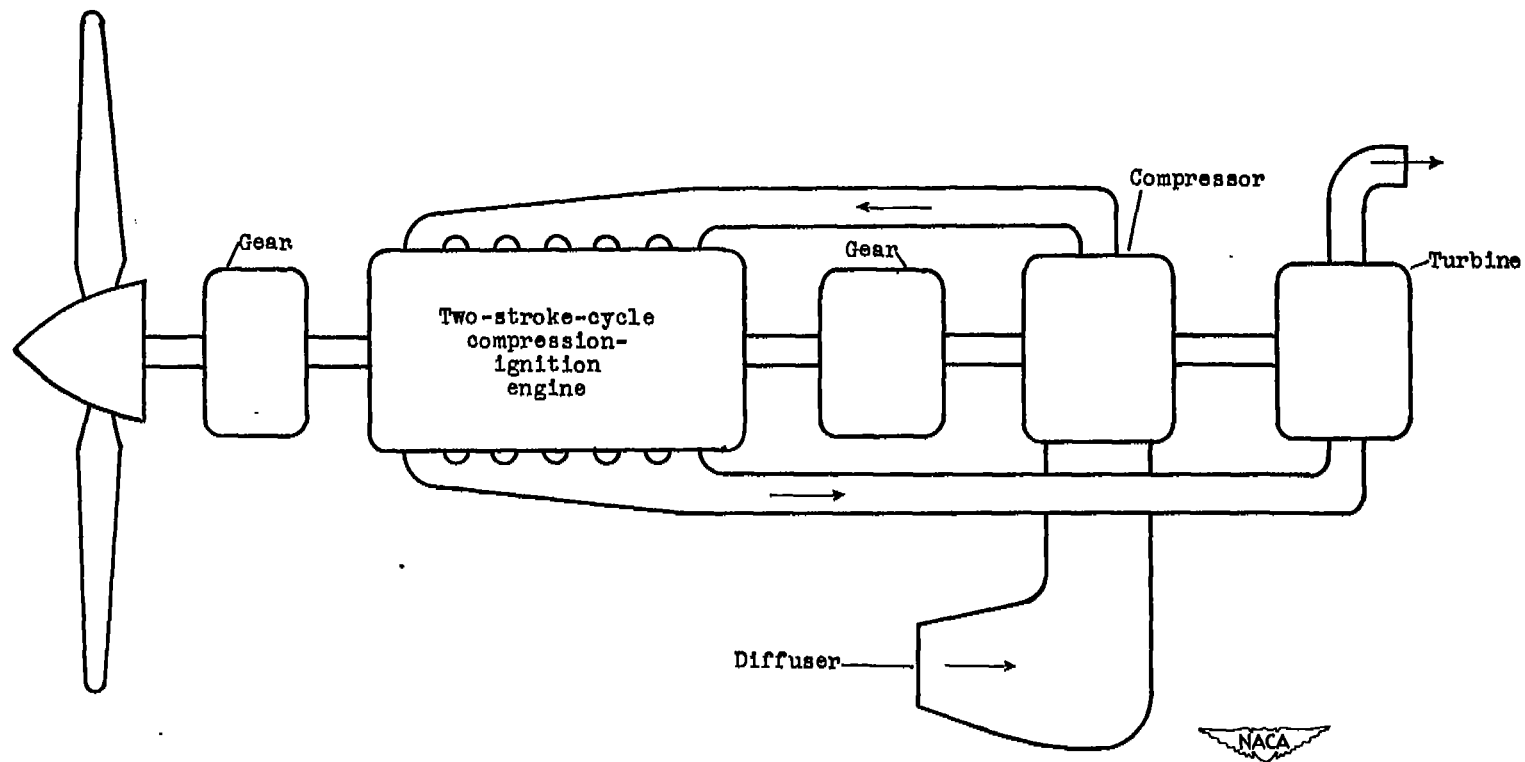


Figure 1. - Diagrammatic sketch of compound engine used in analysis.

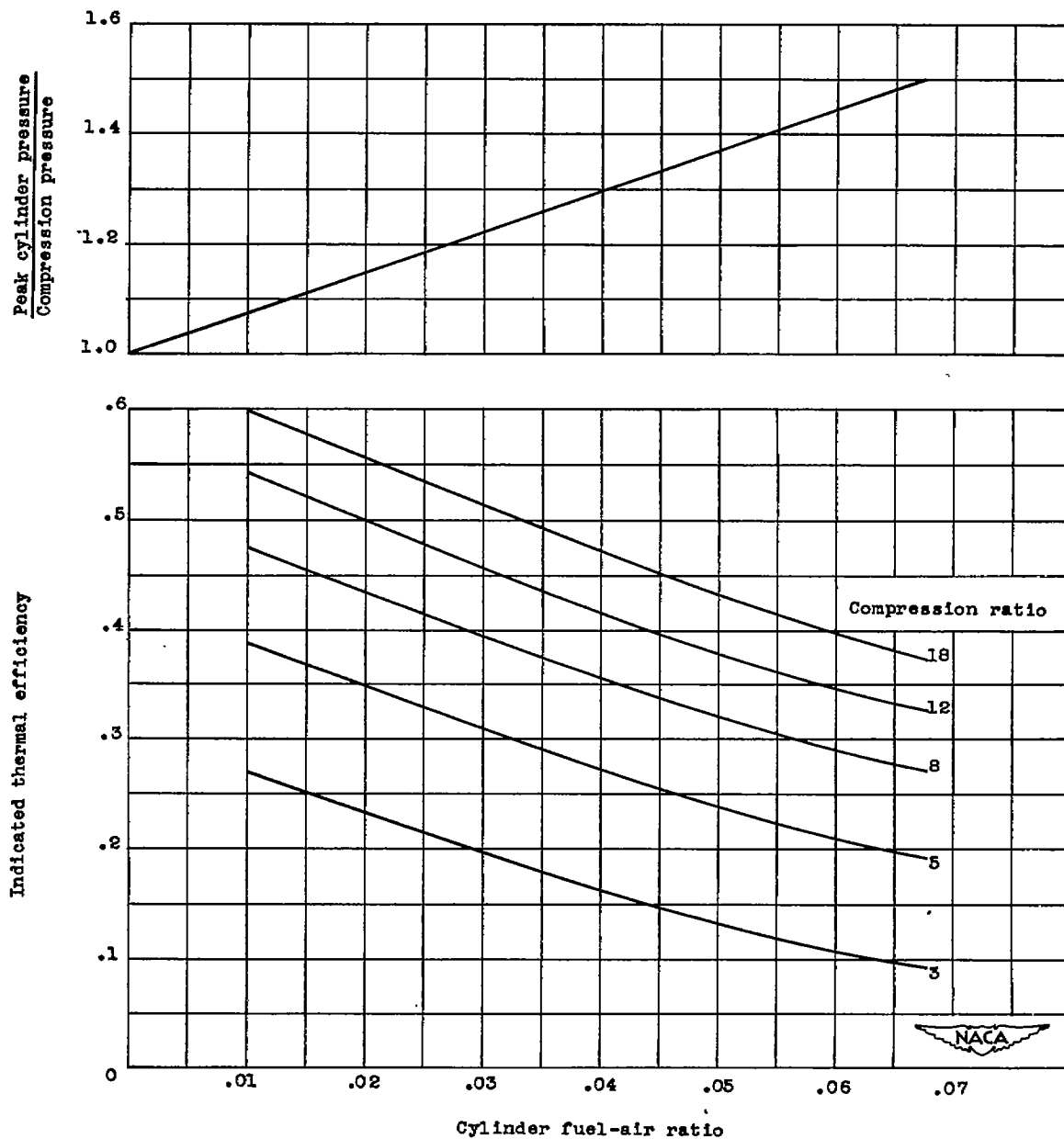


Figure 2. - Peak-cylinder-pressure and efficiency data used for component engine in analysis.

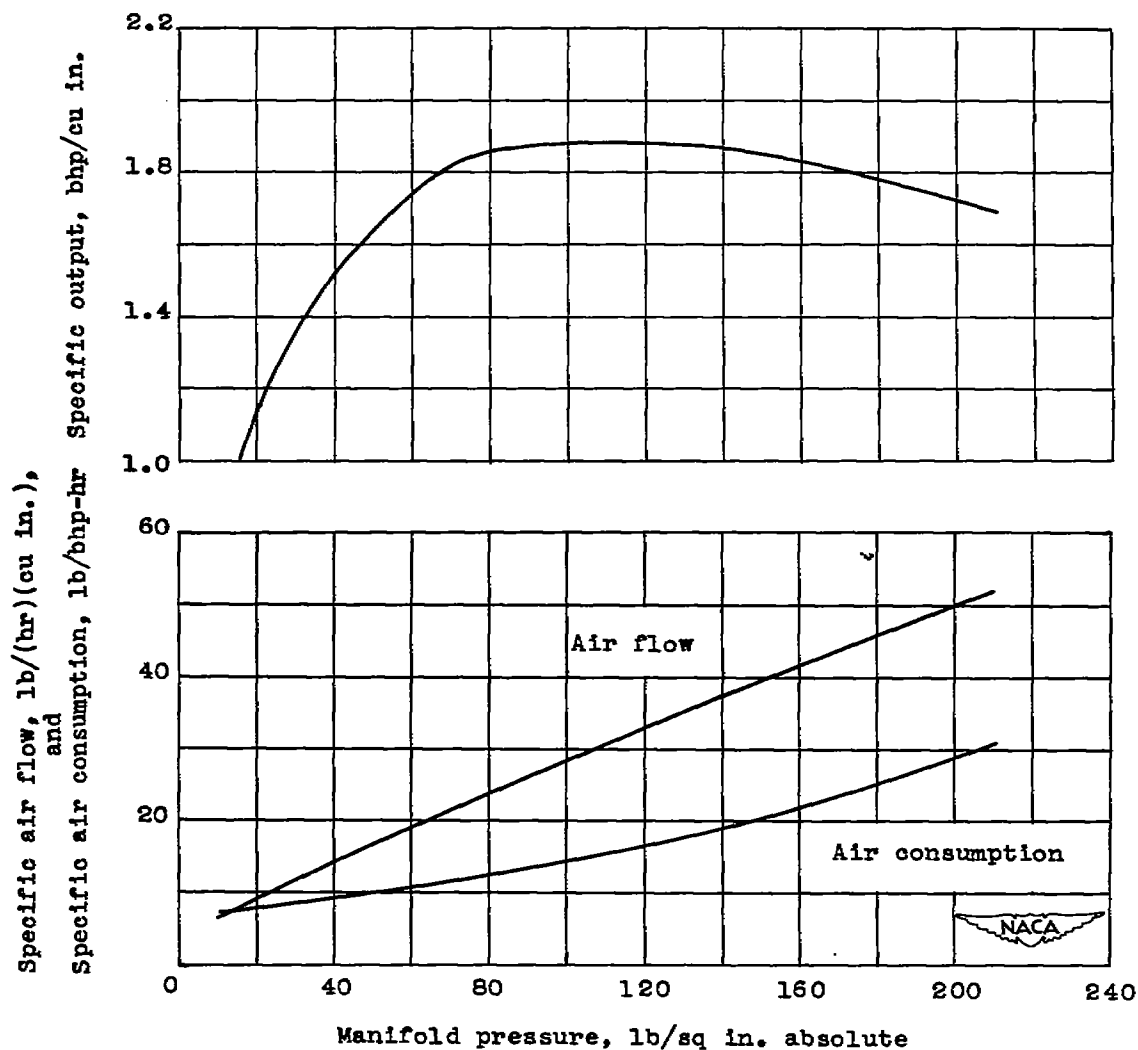


Figure 3. - Effect of manifold pressure on specific air flow and specific air consumption of compound engine and resultant effects on specific output of compound engine. Peak cylinder pressure, 1200 pounds per square inch; turbine-inlet temperature, 1860° R; altitude, 30,000 feet; flight velocity, 400 miles per hour.

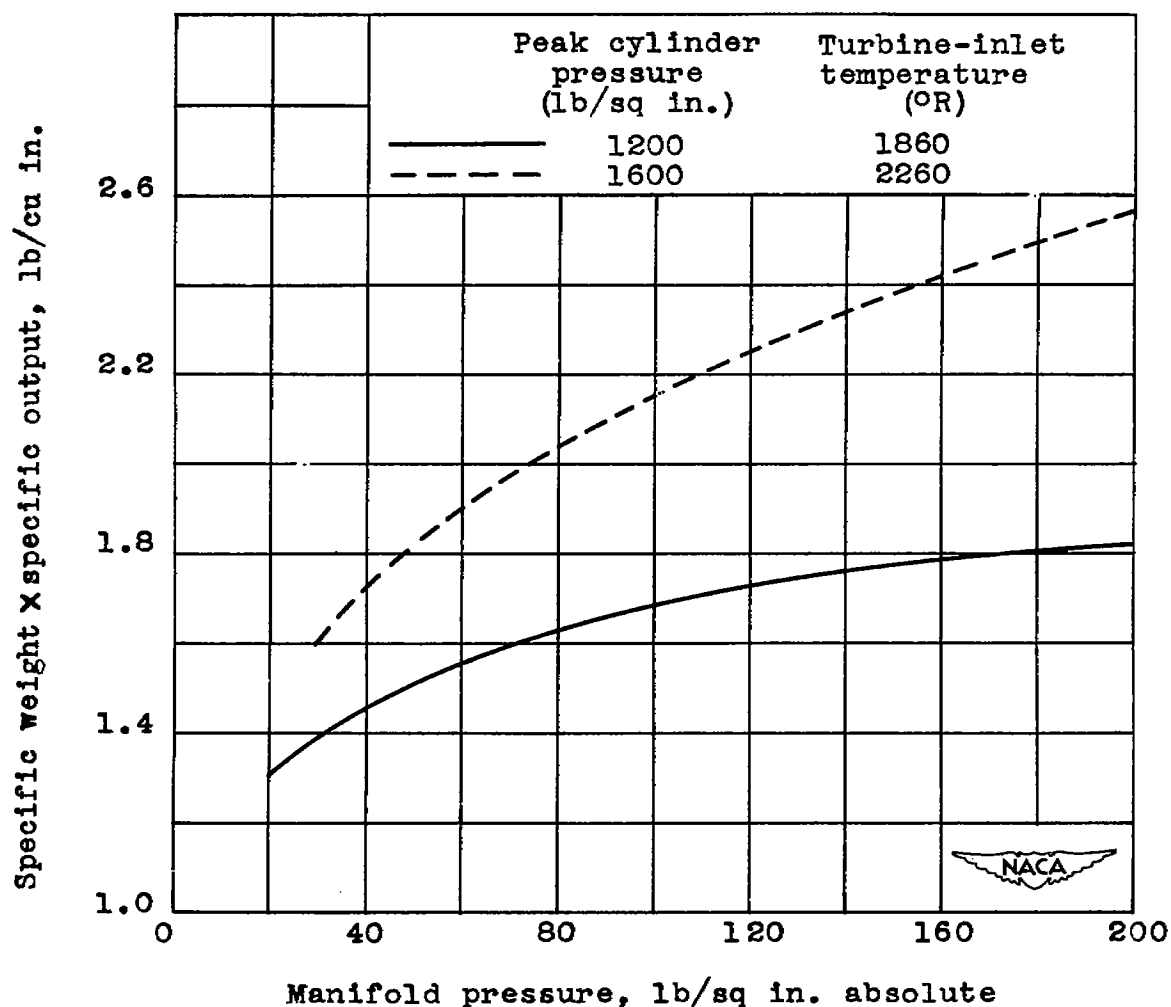


Figure 4. - Variation of product of specific weight and specific output (total engine weight without propeller/cu in. of cylinder volume) with manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour.

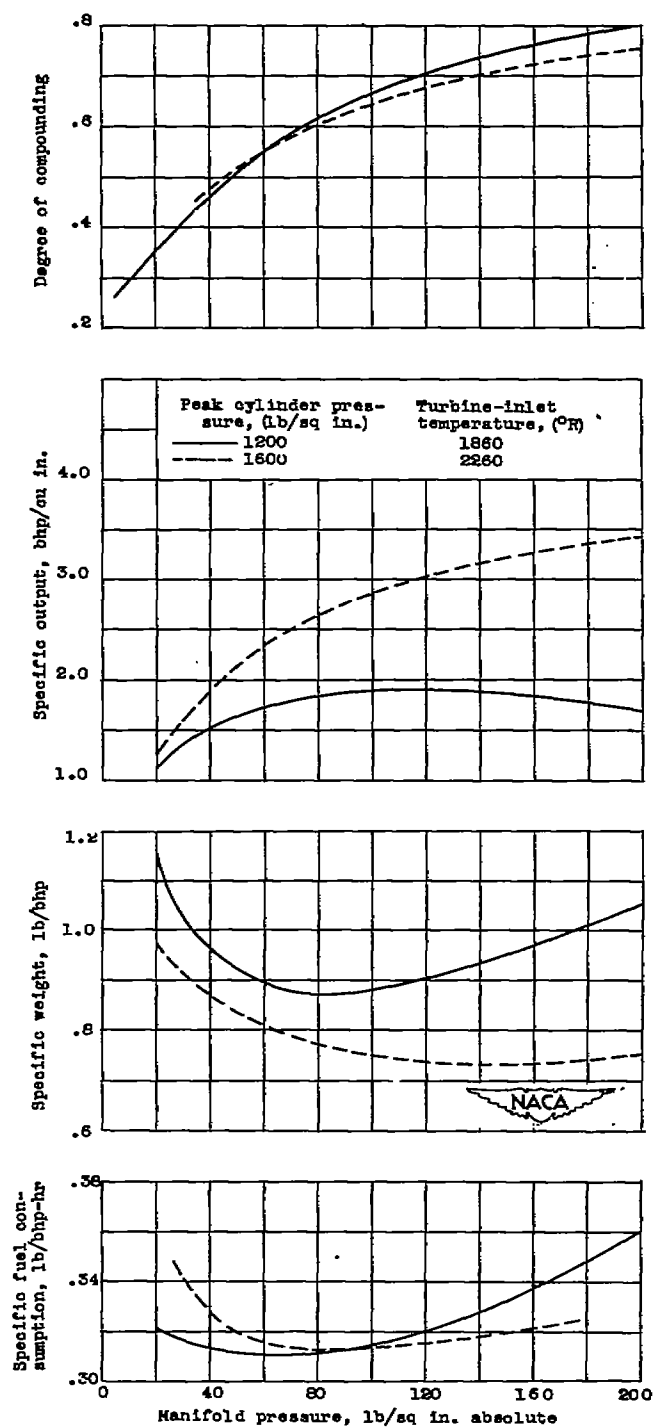
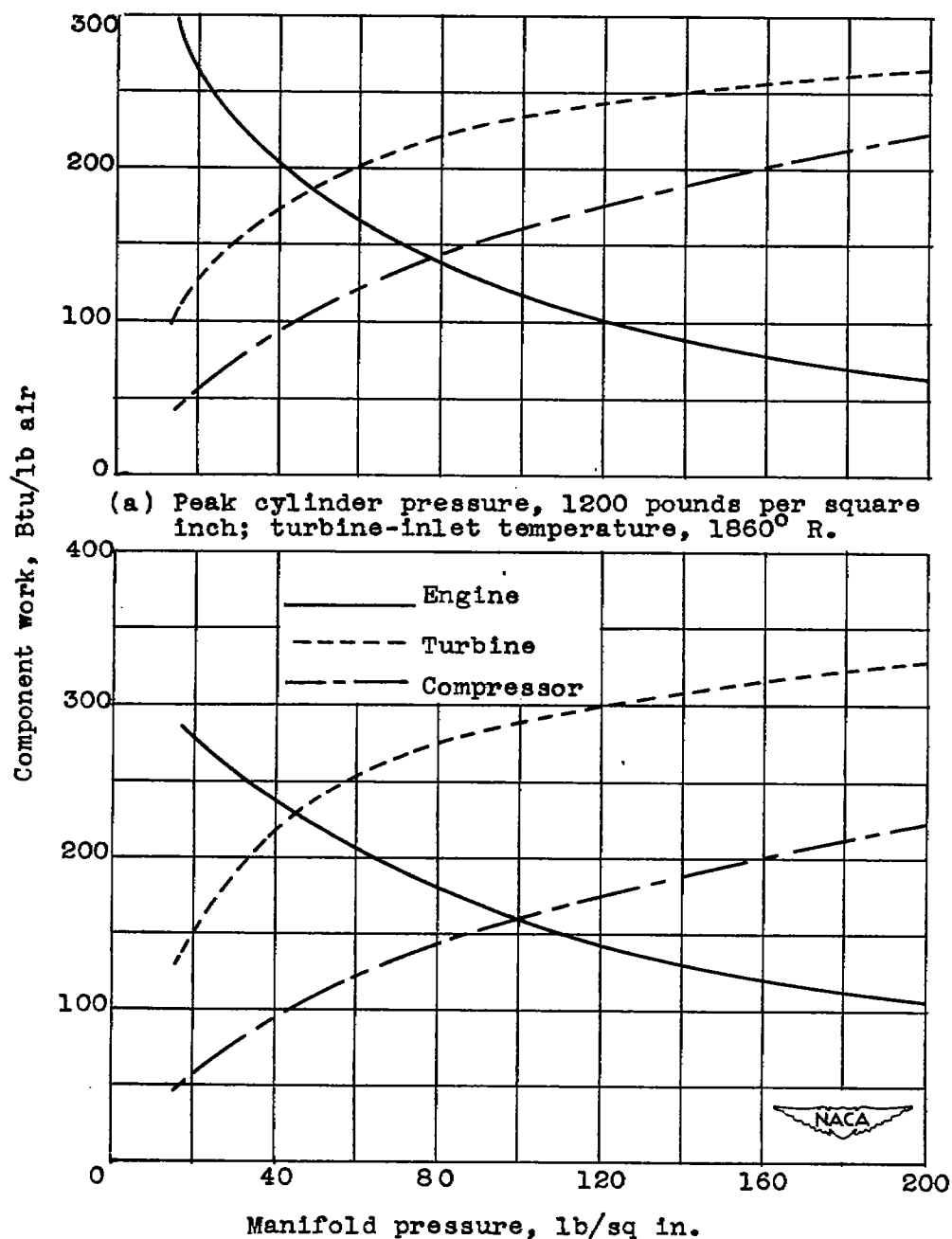


Figure 5. - Effect of manifold pressure on specific weight, specific output, specific fuel consumption, and degree of compounding of compound engine at two values of engine limits. Altitude, 30,000 feet; flight velocity, 400 miles per hour.



(b) Peak cylinder pressure, 1600 pounds per square inch; turbine-inlet temperature, 2260° R.

Figure 6. - Effect of manifold pressure on division of work of compound engine. Altitude, 30,000 feet; flight velocity, 400 miles per hour.

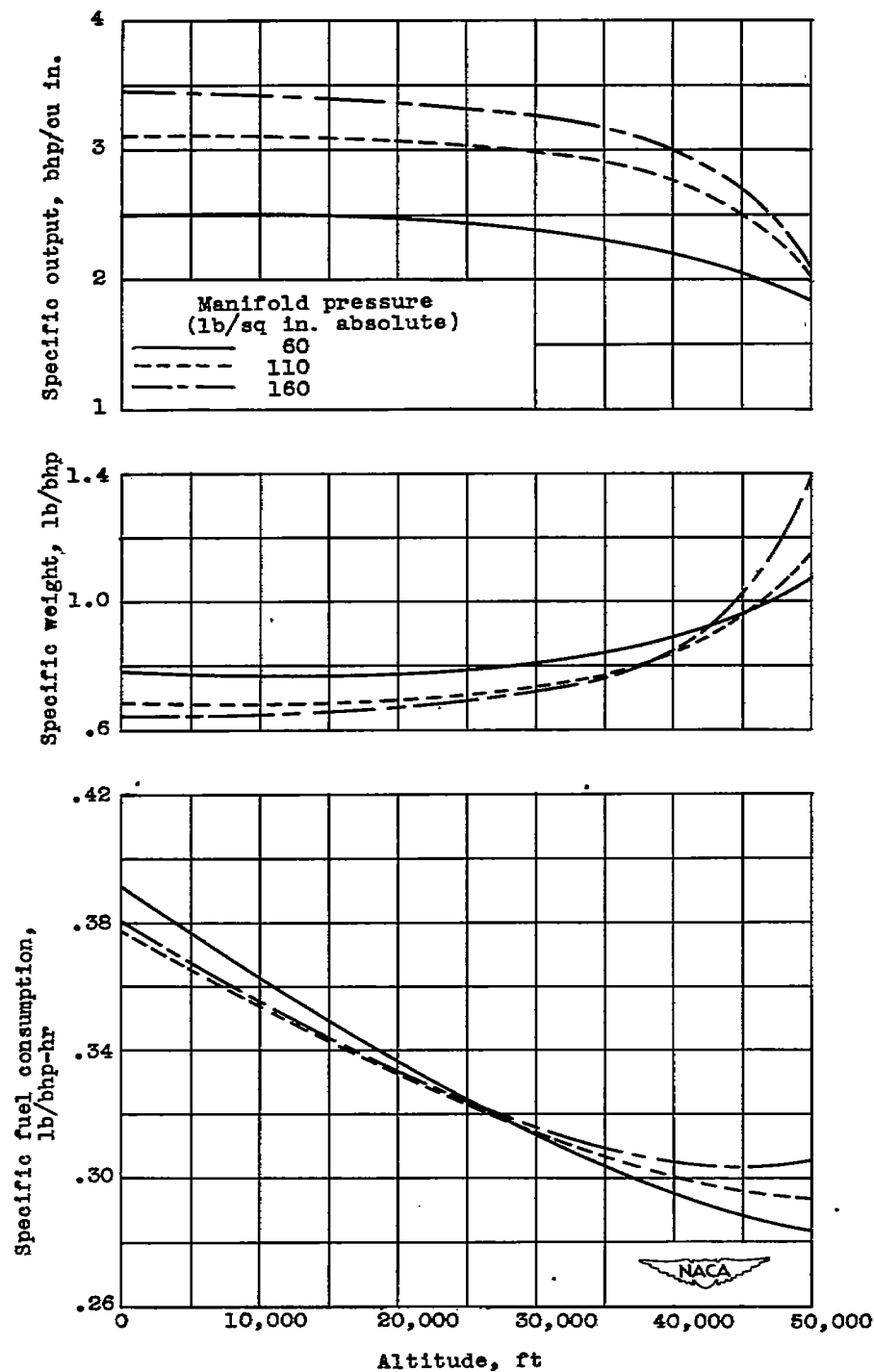


Figure 7. - Effect of altitude on performance of compound engine. Peak cylinder pressure, 1600 pounds per square inch; turbine-inlet temperature, 2260° R; flight velocity, 400 miles per hour.

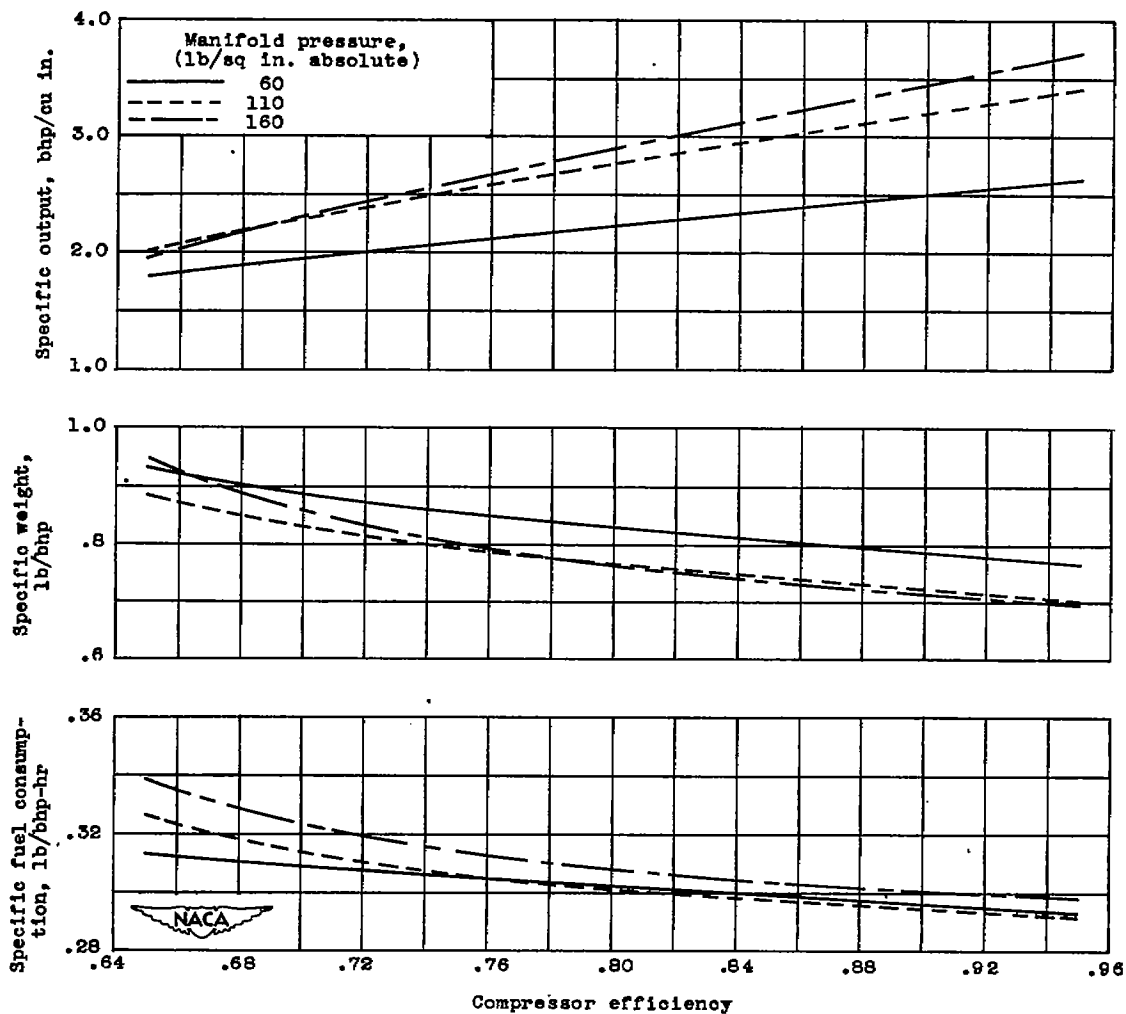


Figure 8. - Effect of compressor efficiency on performance of compound engine. Peak cylinder pressure, 1600 pounds per square inch; turbine-inlet temperature, 2260° R; altitude, 30,000 feet; flight velocity, 400 miles per hour.

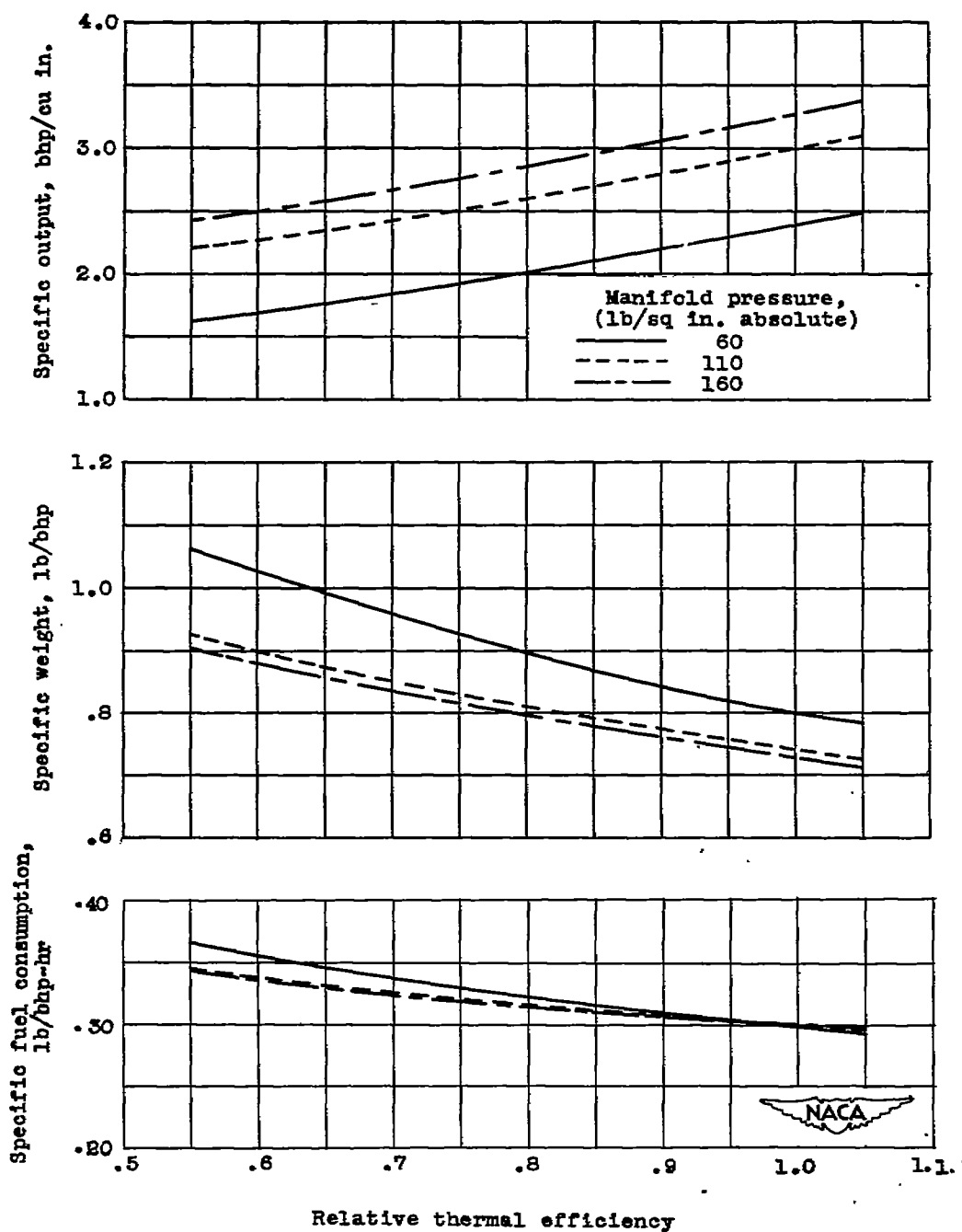


Figure 9. - Effect of relative thermal efficiency of component engine on performance of compound engine. Peak cylinder pressure, 1600 pounds per square inch; turbine-inlet temperature, 2260° R; altitude, 30,000 feet; flight velocity, 400 miles per hour. (Relative thermal efficiency is defined as ratio of the actual component-engine efficiency to that defined by fig. 2.)

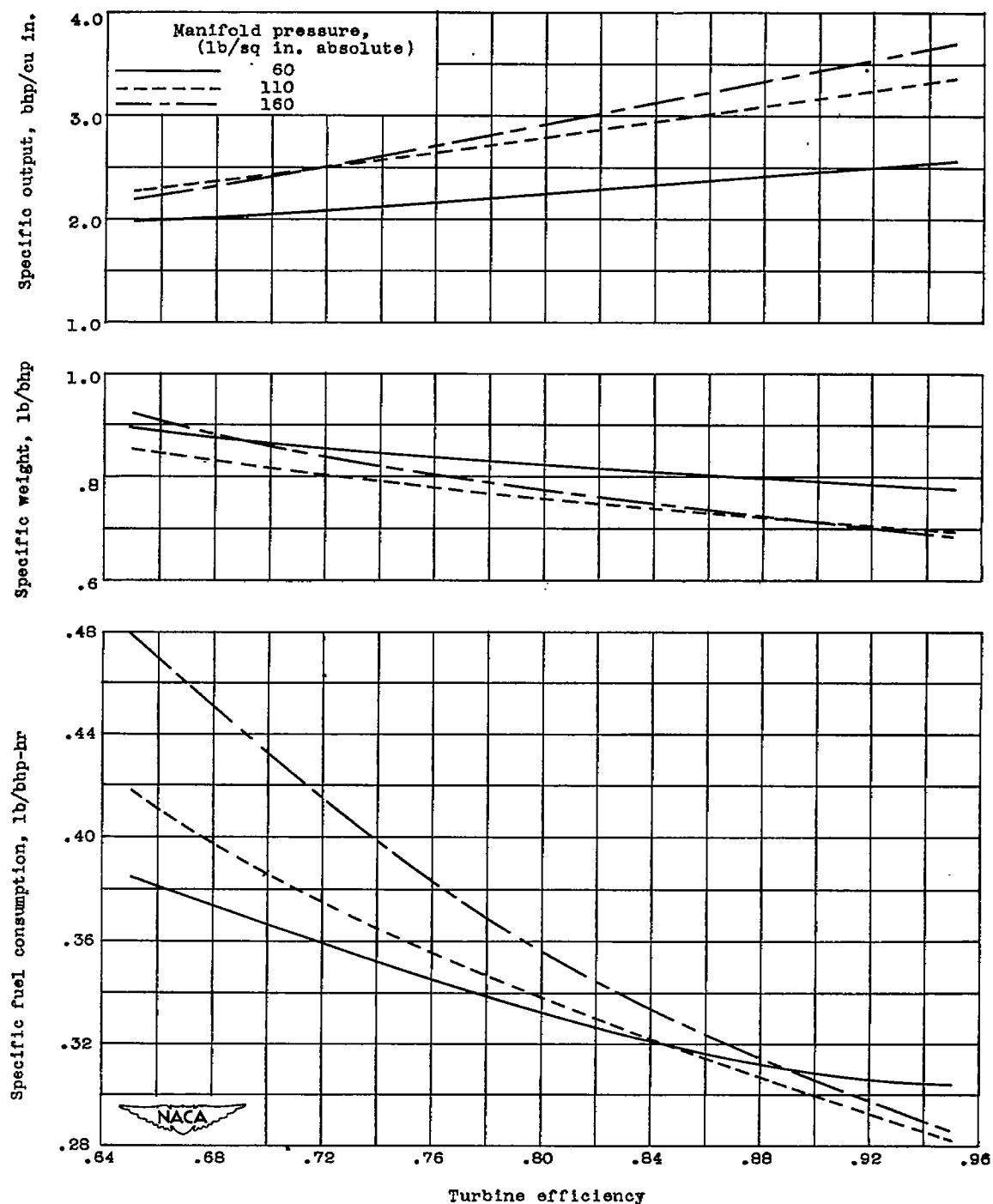
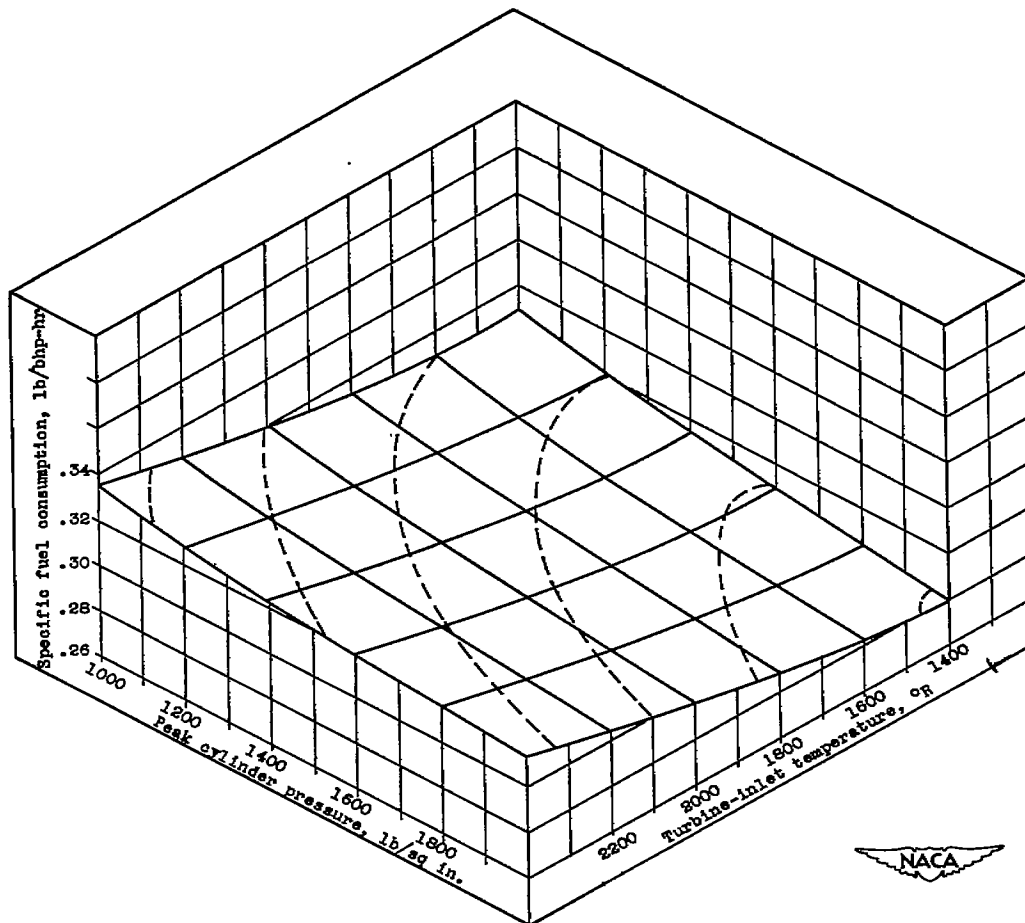
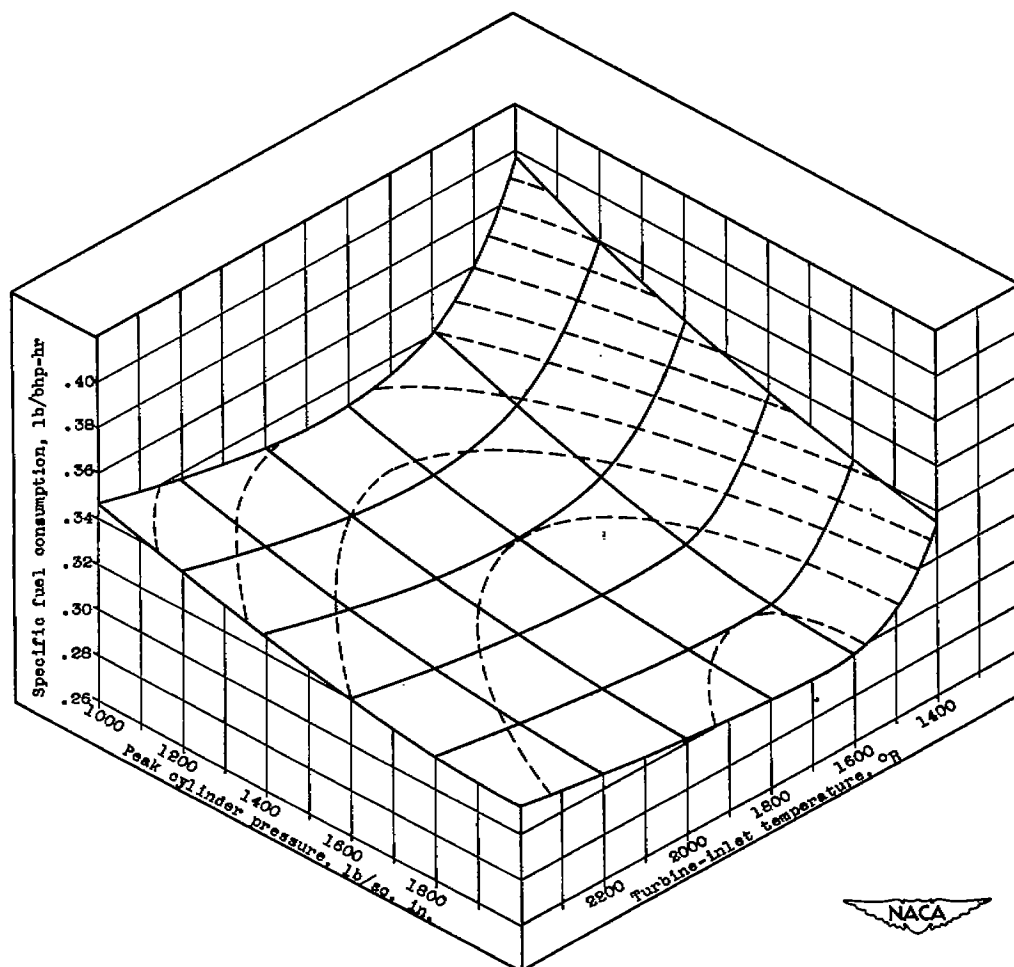


Figure 10. - Effect of turbine efficiency on performance of engine. Peak cylinder pressure, 1600 pounds per square inch; turbine-inlet temperature, 2260° R; altitude, 30,000 feet; flight velocity, 400 miles per hour.



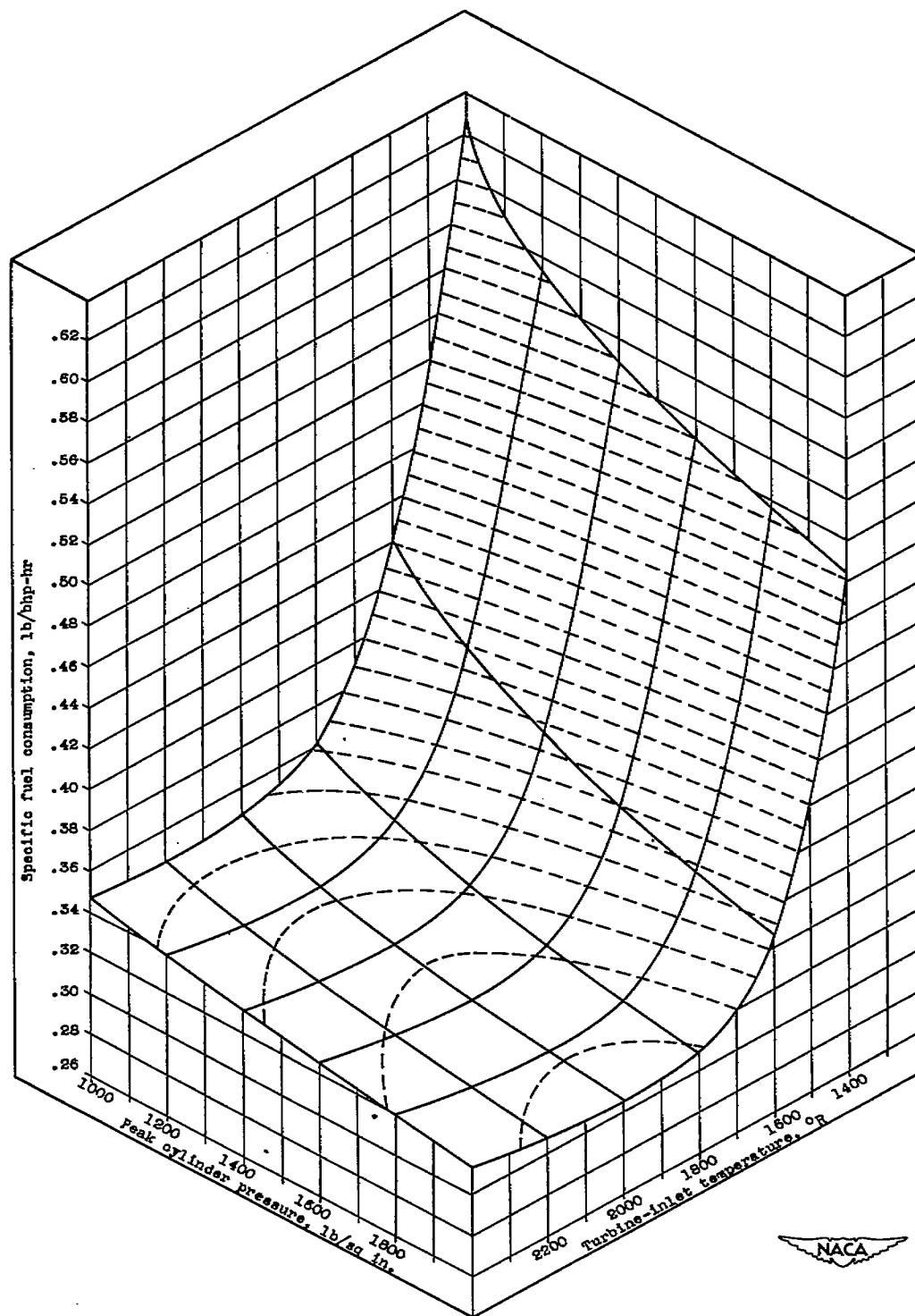
(a) Manifold pressure, 60 pounds per square inch absolute.

Figure 11. - Effect of engine limits on brake specific fuel consumption of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



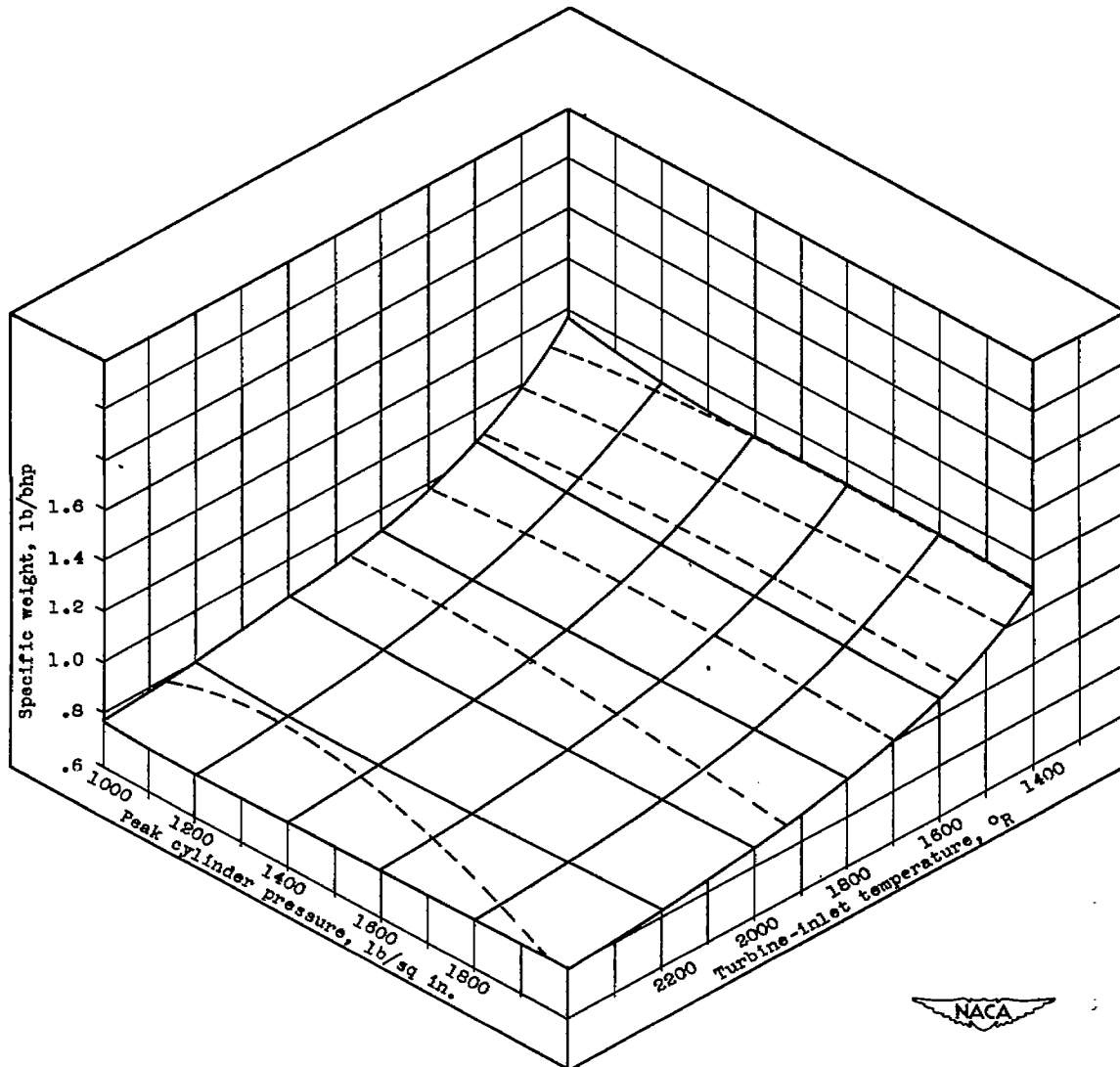
(b) Manifold pressure, 110 pounds per square inch absolute.

Figure 11. - Continued. Effect of engine limits on brake specific fuel consumption of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



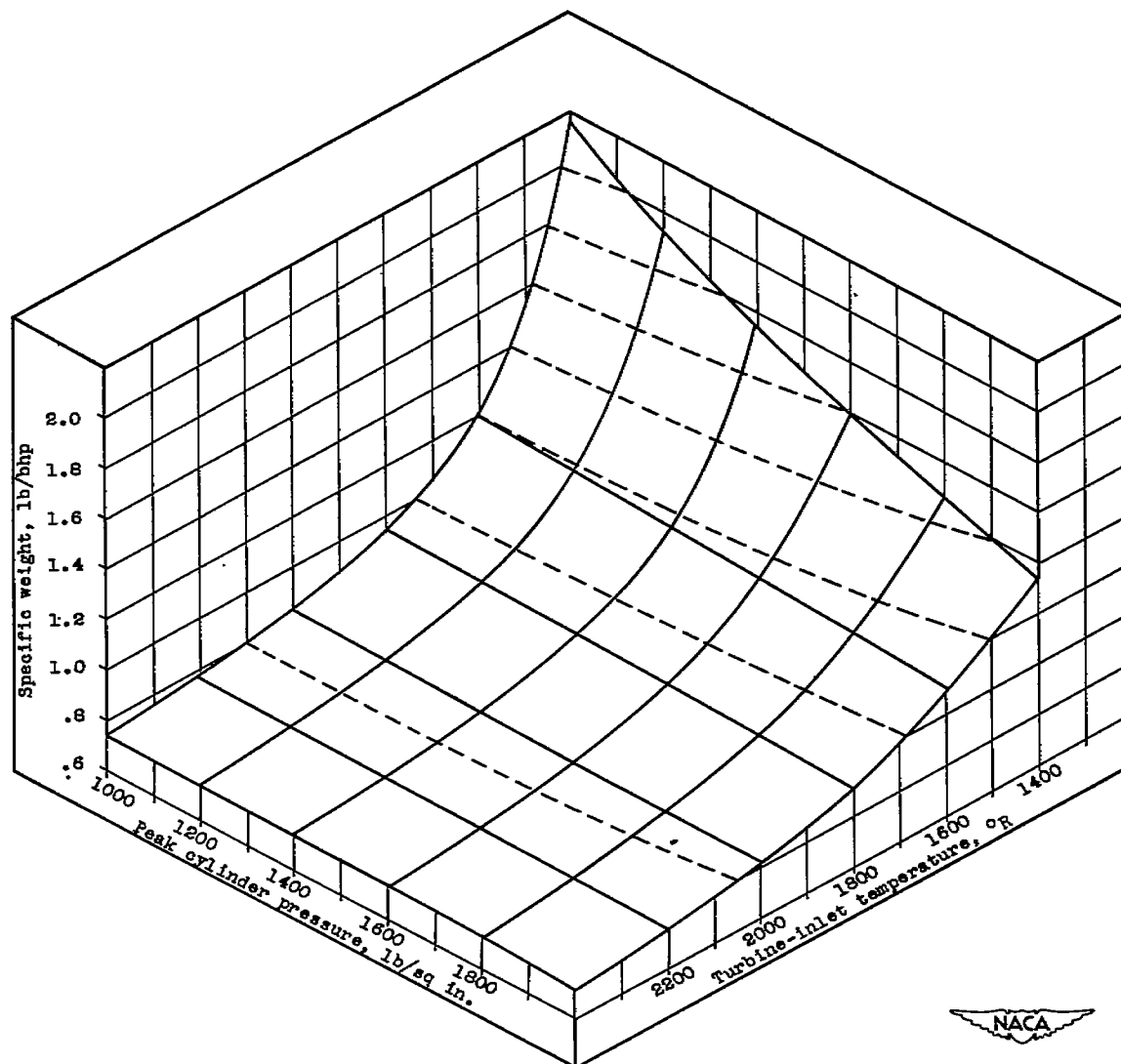
(c) Manifold pressure, 180 pounds per square inch absolute.

Figure 11. - Concluded. Effect of engine limits on brake specific fuel consumption of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



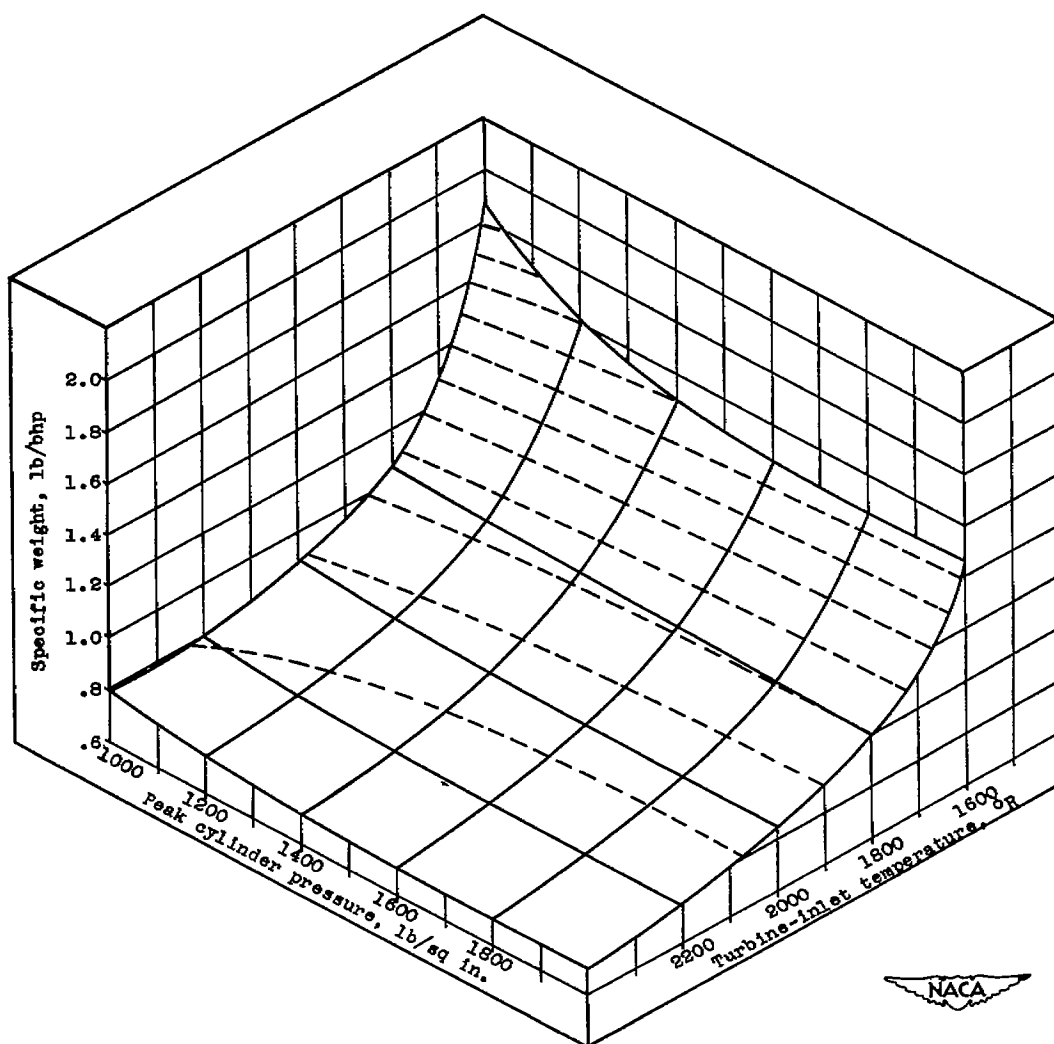
(a) Manifold pressure, 60 pounds per square inch absolute.

Figure 12. - Effect of engine limits on specific weight of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



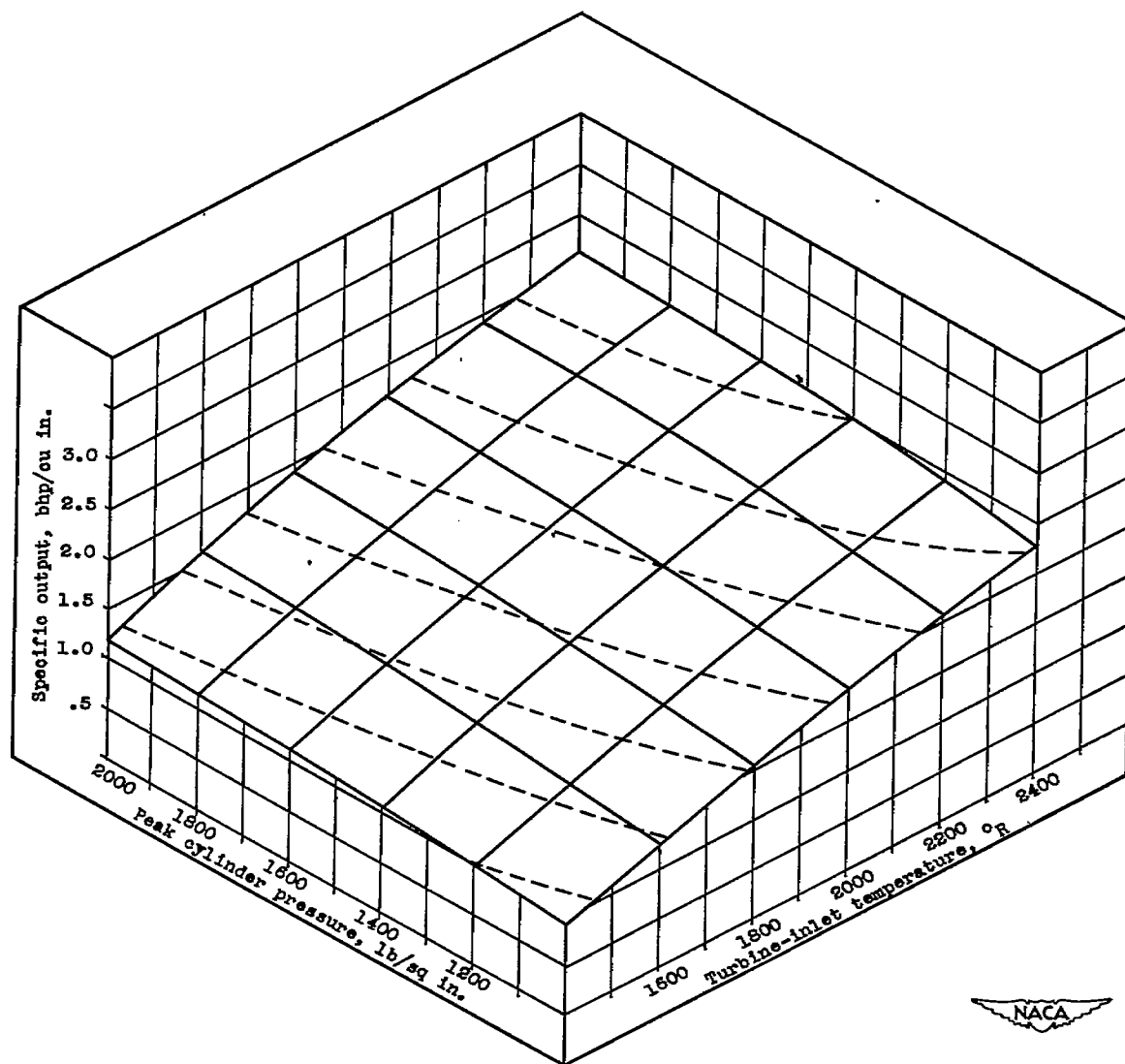
(b) Manifold pressure, 110 pounds per square inch absolute.

Figure 12. - Continued. Effect of engine limits on specific weight of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



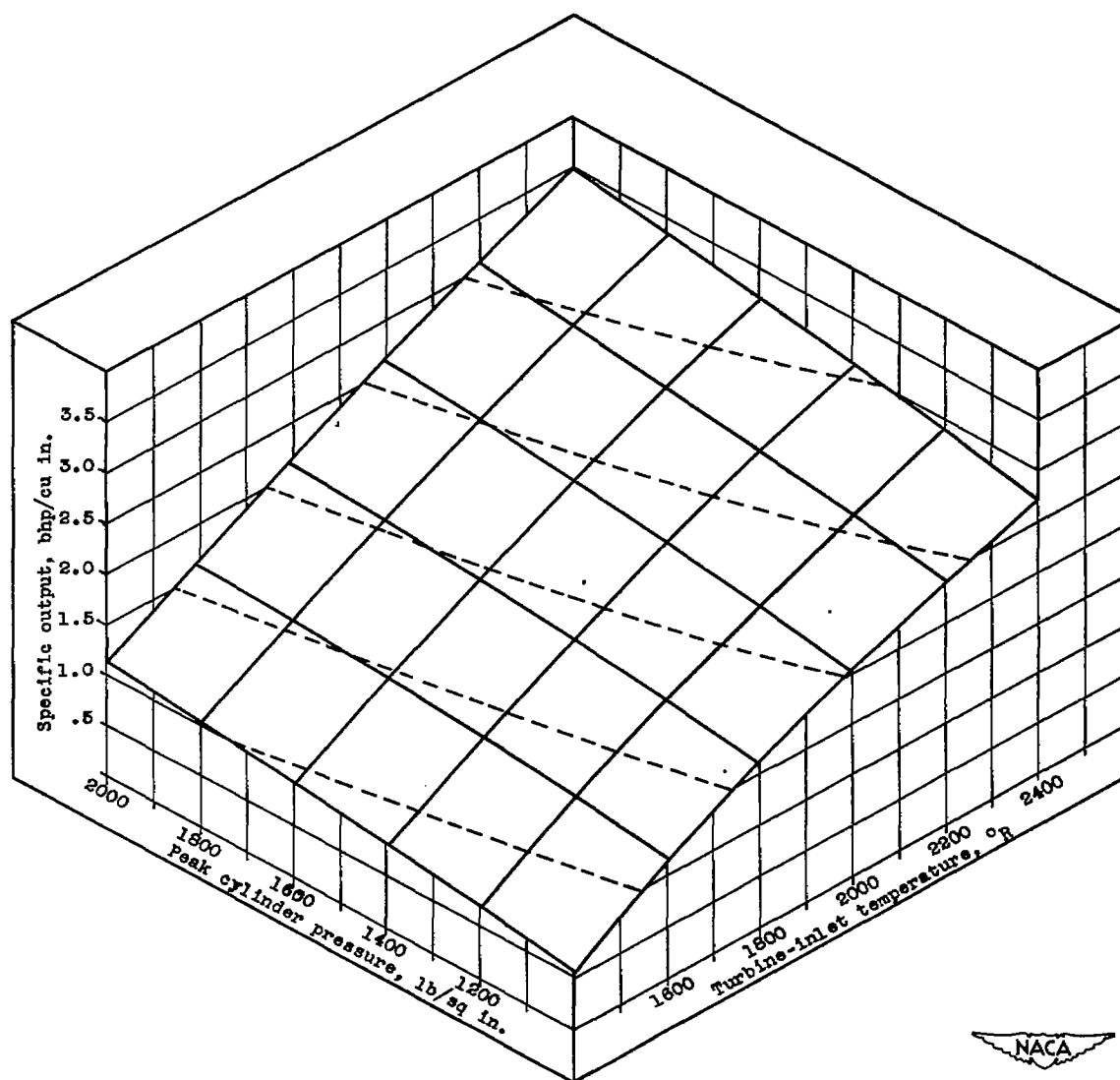
(c) Manifold pressure, 160 pounds per square inch absolute.

Figure 12. - Concluded. Effect of engine limits on specific weight of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



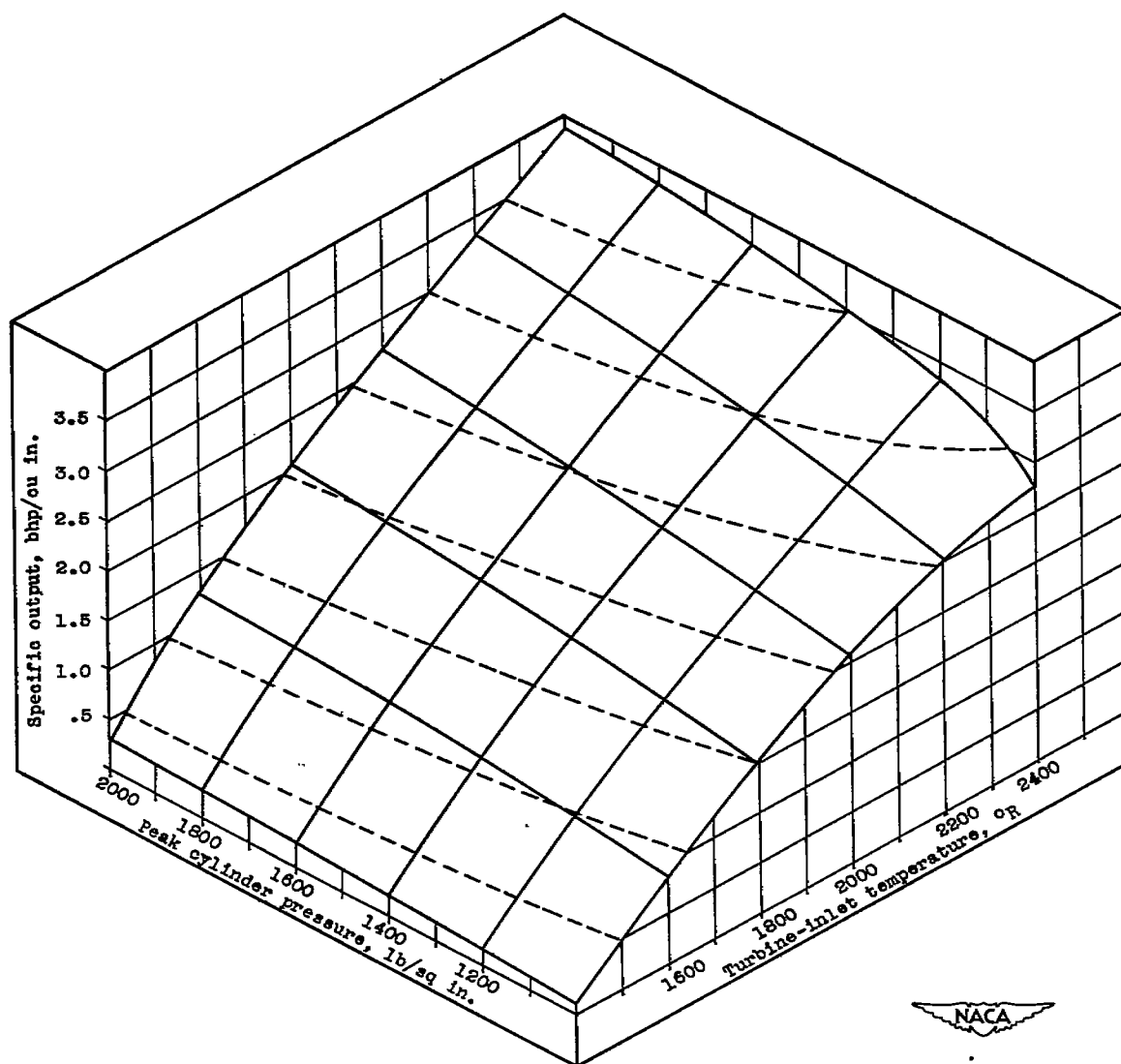
(a) Manifold pressure, 60 pounds per square inch absolute.

Figure 13. - Effect of engine limits on specific output of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



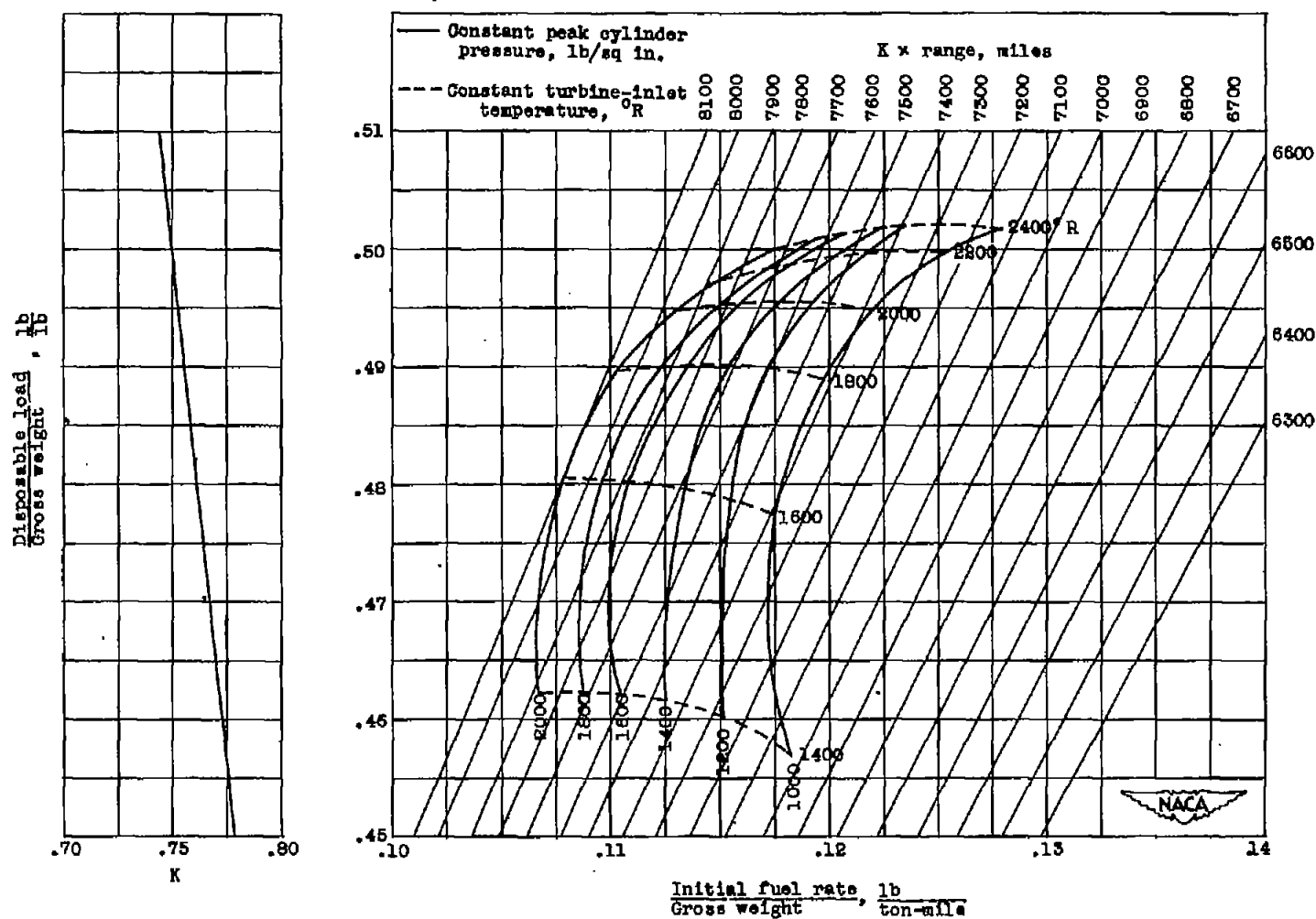
(b) Manifold pressure, 110 pounds per square inch absolute.

Figure 13. - Continued. Effect of engine limits on specific output of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



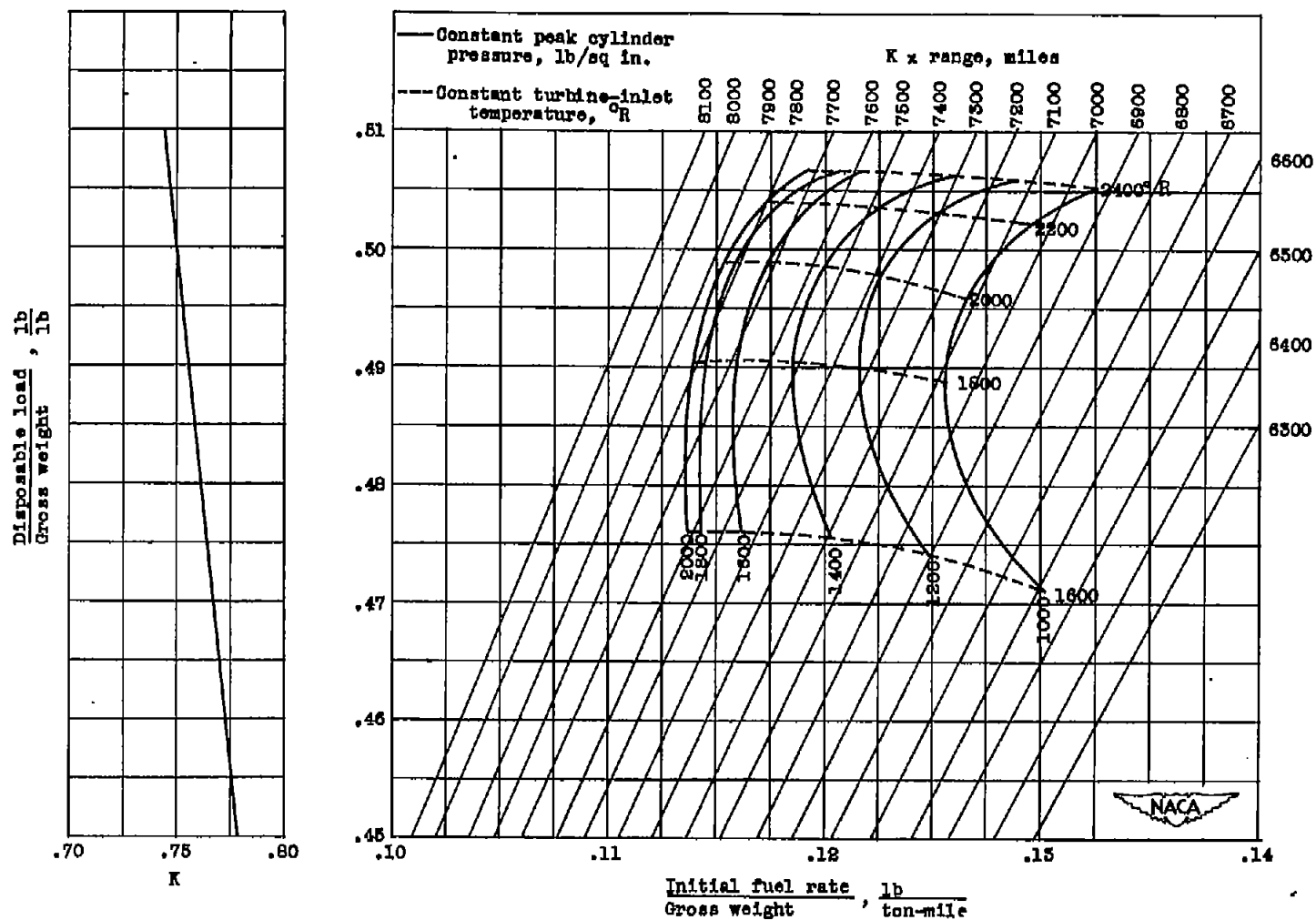
(c) Manifold pressure, 160 pounds per square inch absolute.

Figure 13. - Concluded. Effect of engine limits on specific output of compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Dashed lines represent constant ordinate values.)



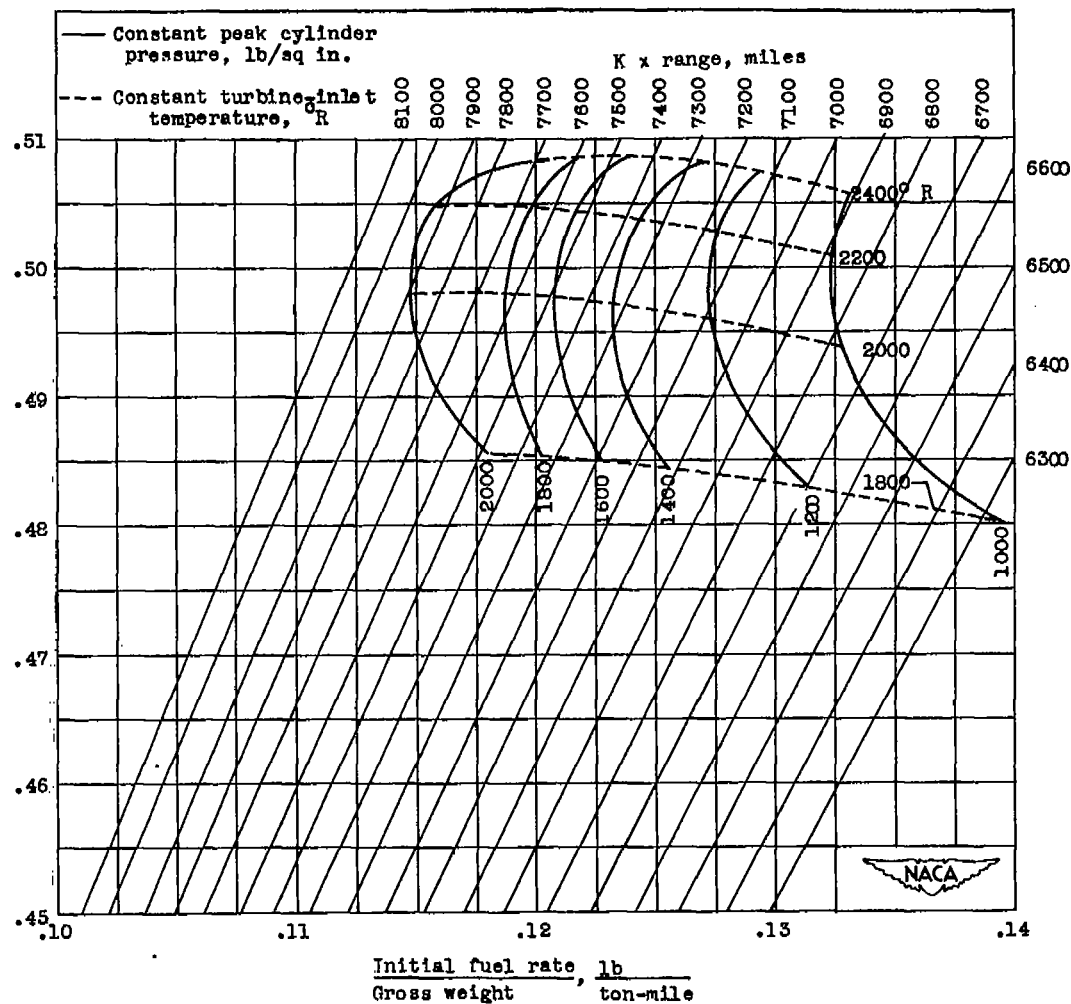
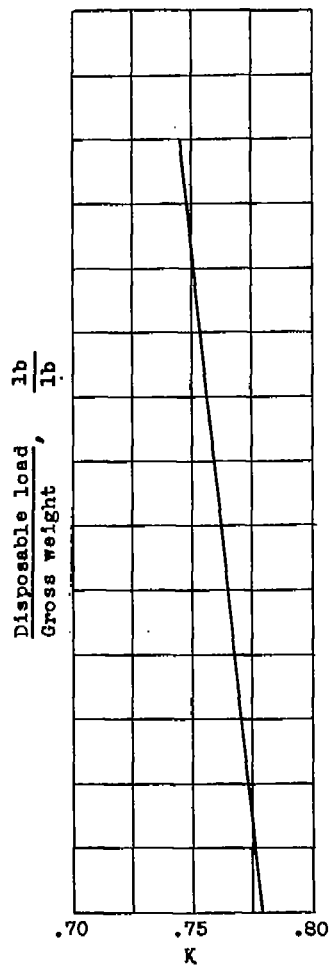
(a) Manifold pressure, 60 pounds per square inch absolute.

Figure 14. - Effect of engine limits on flight range of aircraft with compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Wing loading limited to 80 lb/sq ft.)



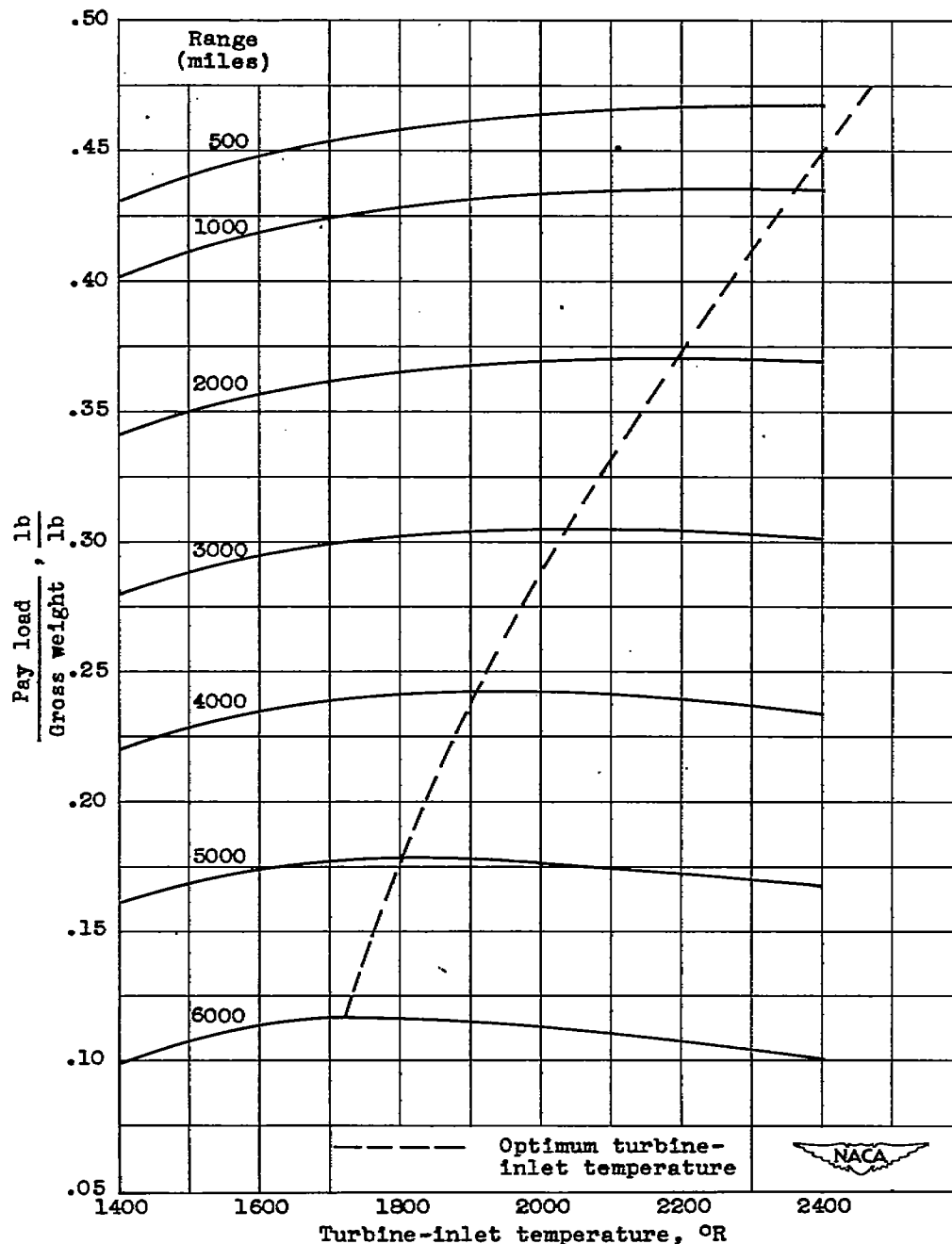
(b) Manifold pressure, 110 pounds per square inch absolute.

Figure 14. - Continued. Effect of engine limits on flight range of aircraft with compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Wing loading limited to 80 lb/sq ft.)



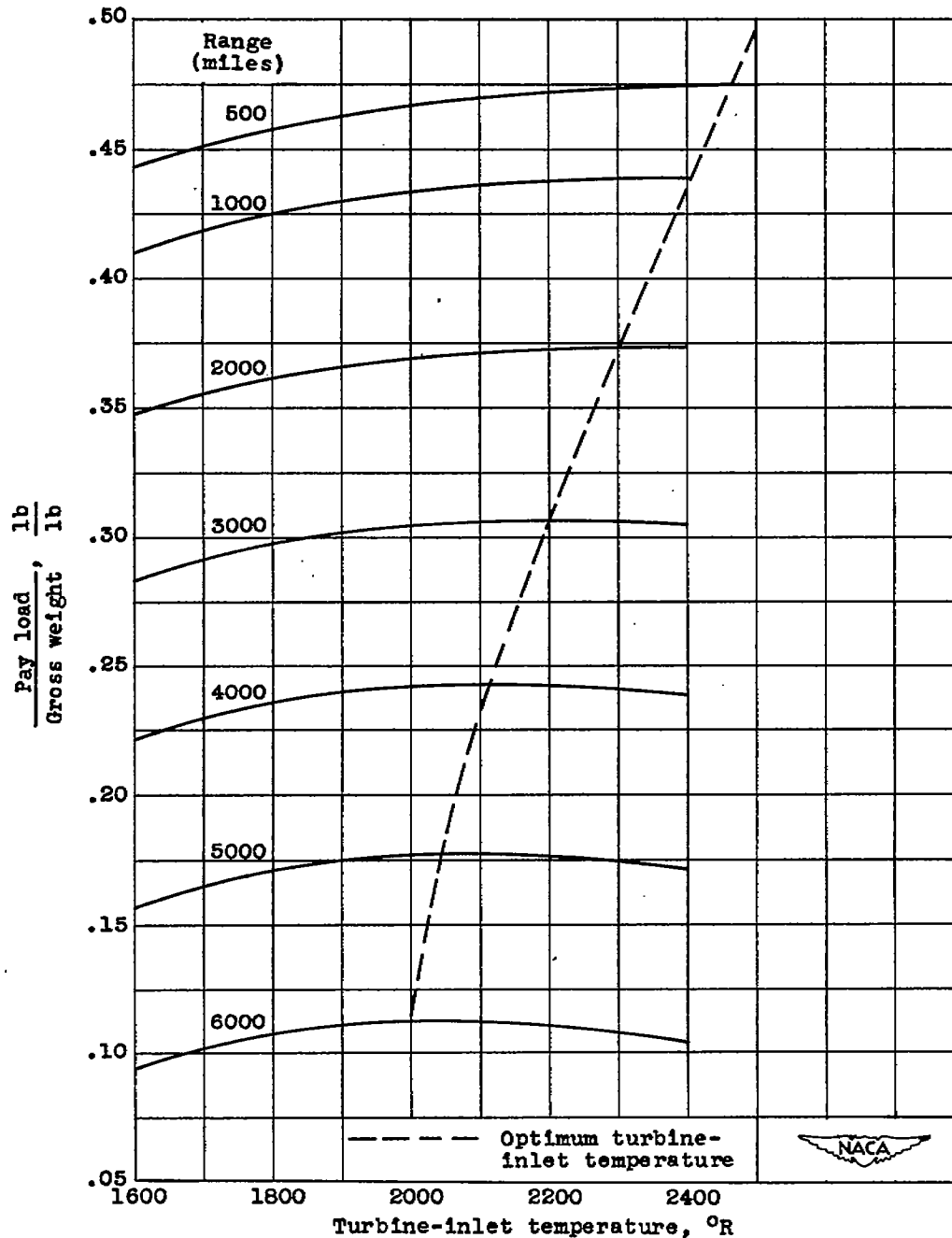
(c) Manifold pressure, 160 pounds per square inch absolute.

Figure 14. - Concluded. Effect of engine limits on flight range of aircraft with compound engine at three values of manifold pressure. Altitude, 30,000 feet; flight velocity, 400 miles per hour. (Wing loading limited to 80 lb/sq ft.)



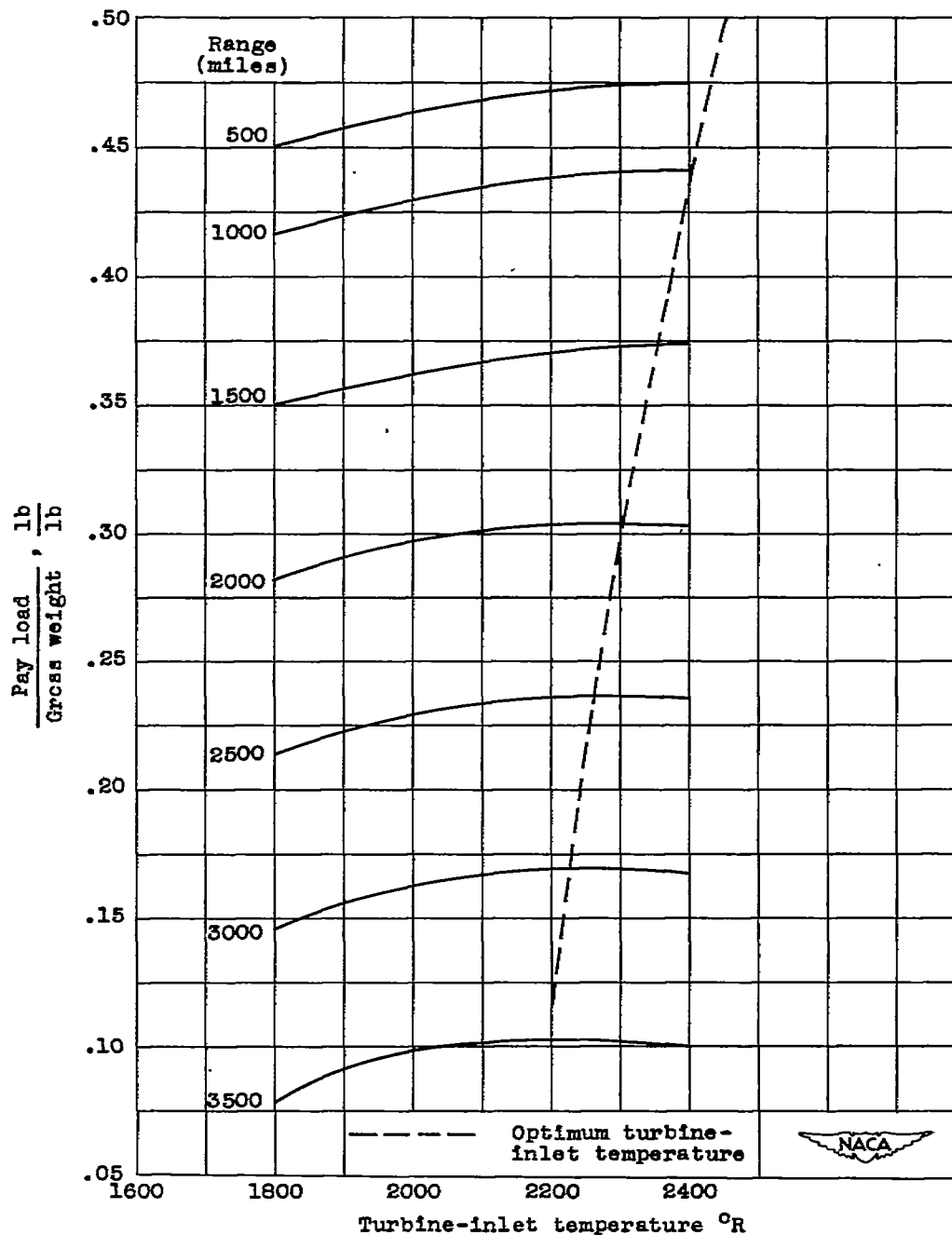
(a) Manifold pressure, 60 pounds per square inch absolute.

Figure 15. - Effect of flight range and turbine-inlet temperature on pay-load capacity at three values of manifold pressure. Peak cylinder pressure, 1600 pounds per square inch; altitude, 30,000 feet; flight velocity, 400 miles per hour. (Wing loading limited to 80 lb/sq in.)



(b) Manifold pressure, 110 pounds per square inch absolute.

Figure 15. - Continued. Effect of flight range and turbine-inlet temperature on pay-load capacity at three values of manifold pressure. Peak cylinder pressure, 1600 pounds per square inch; altitude, 30,000 feet; flight velocity, 400 miles per hour. (Wing loading limited to 80 lb/sq in.)



(c) Manifold pressure, 160 pounds per square inch absolute.

Figure 15. - Concluded. Effect of flight range and turbine-inlet temperature on pay-load capacity at three values of manifold pressure. Peak cylinder pressure, 1600 pounds per square inch; altitude, 30,000 feet; flight velocity, 400 miles per hour. (Wing loading limited to 80 lb/sq in.)

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